SOCIAL COST OF OIL POLLUTION

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THESIS

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by

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The purpose of this thesis is to investigate a mehtod of improving decision making relative to the problems created by oil spillage. Many countries around the world, including Indonesia, are plagued by increasing pollution from these spills.

This thesis uses a simulation to consider the spread and damage caused by oil spills using data from San Francisco Bay. A projection of social costs

20. from these spills has been made.

Formulation of a methodology for deriving the social cost of oil spills is a prerequisite in reaching optimal, rational decisions in managing oil pollution. Such decisions may include the establishment of a fine structure, determination of the required level of clean-up and identification of socially significant spills.

SOCIAL COST OF OIL POLLUTION

BY

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A B S T R A C T

THE PURPOSE OF THIS THESIS IS TO INVESTIGATE A METHOD OF IMPROVING DECISION MAKING RELATIVE TO THE PROBLEMS CREATED BY OIL SPILLAGE. MANY COUNTRIES AROUND THE WORLD, INCLUDING INDONESIA, ARE PLAGUED BY INCREASING POLLUTION FROM THESE SPILLS.

THIS THESIS USES A SIMULATION TO CONSIDER THE SPREAD AND DAMAGE CAUSED BY OIL SPILLS USING DATA FROM SAN FRANCISCO BAY. A PROJECTION OF SOCIAL COSTS FROM THESE SPILLS HAS BEEN MADE.

FORMULATION OF A METHODOLOGY FOR DERIVING THE SOCIAL COST OF OIL SPILLS IS A PREREQUISITE IN REACHING OPTIMAL, RATIONAL DECISIONS IN MANAGING OIL POLLUTION. SUCH DECISIONS MAY INCLUDE THE ESTABLISHMENT OF A FINE STRUCTURE, DETERMINATION OF THE REQUIRED LEVEL OF CLEAN-UP AND IDENTIFICATION OF SOCIALLY SIGNIFICANT SPILLS.

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I. I N T R O D U C T I O N .

MAN HAS BEEN POLLUTING THE WATERS OF THE WORLD FOR YEARS. UNTIL THE ECOLOGY MOVEMENT AND THE PRESENT RESOURCE CONSERVATION PROGRAM, LITTLE CONCERTED EFFORT HAS BEEN MADE TO REDUCE POLLUTION.

SINCE 1970, THE U.S. ENVIRONMENTAL PROTECTION AGENCY HAS PLAYED A MAJOR ROLE IN ATTEMPTS TO REDUCE THE FREQUENCY OF OIL AND HAZARDOUS SUBSTANCE SPILLS AND TO MINIMIZE ENVIRONMENTAL DAMAGE CAUSED BY THOSE SPILLS THAT DO OCCUR.

IN ADDITION, THE U.S. COAST GUARD HAS BEEN INCREASING ITS EFFORTS IN DETECTION AND CLEANING OF HAZARDOUS SUBSTANCES SPILLED INTO BODIES OF WATER.

OVER 13,000 SPILLS OF OIL (REF-8) AND HAZARDOUS SUBSTANCES OCCUR ANNUALLY. SPILLED INTO RIVERS, STREAMS, COASTAL WATERS ESTUARIES AND LAKES, OIL SPREAD IN A MATTER OF MINUTES BY THE FORCE OF CURRENT INDUCED BY THE WIND,SALINITY AND TIDES. SPILLS NOT ONLY REPRESENT WASTED RESOURCES BUT CREATE SOCIAL COSTS TO THE SOCIETY NEARBY DIRECTLY AND INDIRECTLY.

OIL POLLUTION IS THE ALMOST INEVITABLE CONSEQUENCE OF THE DEPENDENCE OF GROWING POPULATION ON AN INCREASINGLY OIL-BASED TECHNOLOGY.

BECAUSE OF THE LARGE QUANTITIES OFTEN INVOLVED IN SPILLS, THE EFFECTS ARE NOT ALWAYS COMPARABLE TO THOSE CAUSED BY THE CHRONIC POLLUTION OF INDUSTRIAL AND MUNICIPAL DISCHARGES. SOME OF THE EFFECTS ARE OBVIOUS, SUCH AS POLLUTED BEACHES, RIVERS DOTTED WITH OIL SLICKS, DEAD BIRDS AND FISH .

BUT THE ECOLOGICAL EFFECTS FROM SPILLS ARE NOT CONFINED TO THE IMMEDIATE OR OBVIOUS SINCE OVER A LONG PERIOD OIL SPILLS COULD CHANGE THE COMPOSITION OF AQUATIC COMMUNITIES OR DAMAGE THE ABILITY OF THE SPECIES TO SURVIVE.

THIS STUDY WILL ADDRESS THE PROBLEM OF INCORPORATING A SOCIAL COST FIGURE ON THE CONDITIONS SURROUNDING AN OIL SPILL. IT EMPHASIZES THE PROBLEM OF OIL POLLUTION IN THE SAN FRANCISCO BAY AREA AND ITS RELATED SOCIAL COST. A PREDICTION OF SOCIAL COST HAS BEEN MADE USING COMPUTER SIMULATION WITH

PROBABLE, BUT ARTIFIAL, INPUT DATA.

II. FREQUENCY OF OIL SPILL

A. OIL POLLUTION IN THE WATERS OF THE UNITED STATES.

THIS SECTION WILL STATISTICALLY SHOW OIL POLLUTION IN U.S. WATERS: TYPE OF DISCHARGE, LOCATION OF THE DISCHARGE AND THE SOURCES OF THE DISCHARGE. DATA PRESENTED IN TABLE ONE AND FIGURES ONE THROUGH THREE IS BASED ON THE U.S. COAST GUARD POLLUTION INCIDENT REPORTING SYSTEM (PIRS).
MACRO DATA OF OIL POLLUTION TRENDS IS GIVEN BY TABLE-1 WHICH CONTAINS STATISTICS FOR CALENDAR YEARS 1971 TO 1974.
OIL POLLUTION INCIDENTS OCCURING IN 1973 AND 1974 BY AREA AND LOCATION ARE SHOWN IN FIGURE-1 AND FIGURE-2.
THE LEADING SOURCES EACH YEAR IN THE TOTAL VOLUME DISCHARGED ARE THOSE WHICH HANDLE LARGE VOLUME OF PETROLEUM PRODUCTS, SUCH AS TANKERS, REFINERIES ETC.
FIGURE-3 SHOWS THE RELATIVE VOLUME DISCHARGED INCLUDING ONLY DISCHARGES OVER 100,000 GALLONS (OR 378,500 LITERS) IN 1973 AND 1974.

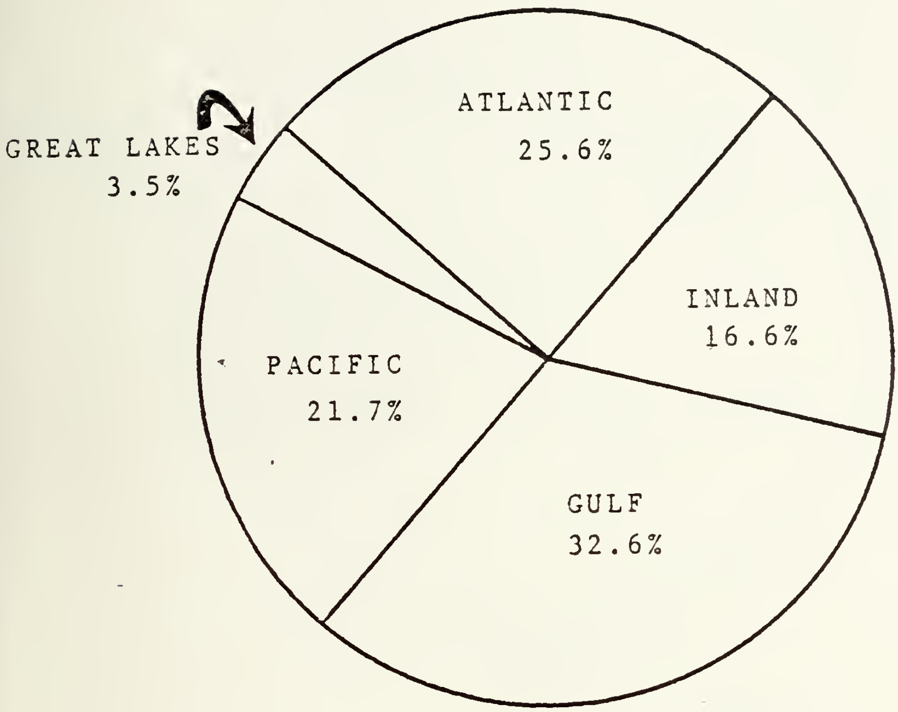
POLLUTION TRENDS IN ALL U. S. WATERS
CALENDAR YEARS 1971 - 1974

	1971	1972	1973	1974
Total Number of Discharges	8,736	9,931	13,327	13,966
Total Volume Discharged	8,839,523	18,805,732	18,314,918	18,132,638
Number of Oil Discharges	7,522	8,380	11,003	11,440
Volume of Oil Discharged (gallons)	8,635,395	16,764,721	15,142,746	15,801,794
Average Amount of Oil Discharged (gallons)	1,148	2,000	1,349	1,381

=TABLE-1=

Source : U.S. Coast Guard P.I.R.S. (Ref-2)

POLLUTION INCIDENTS BY AREA



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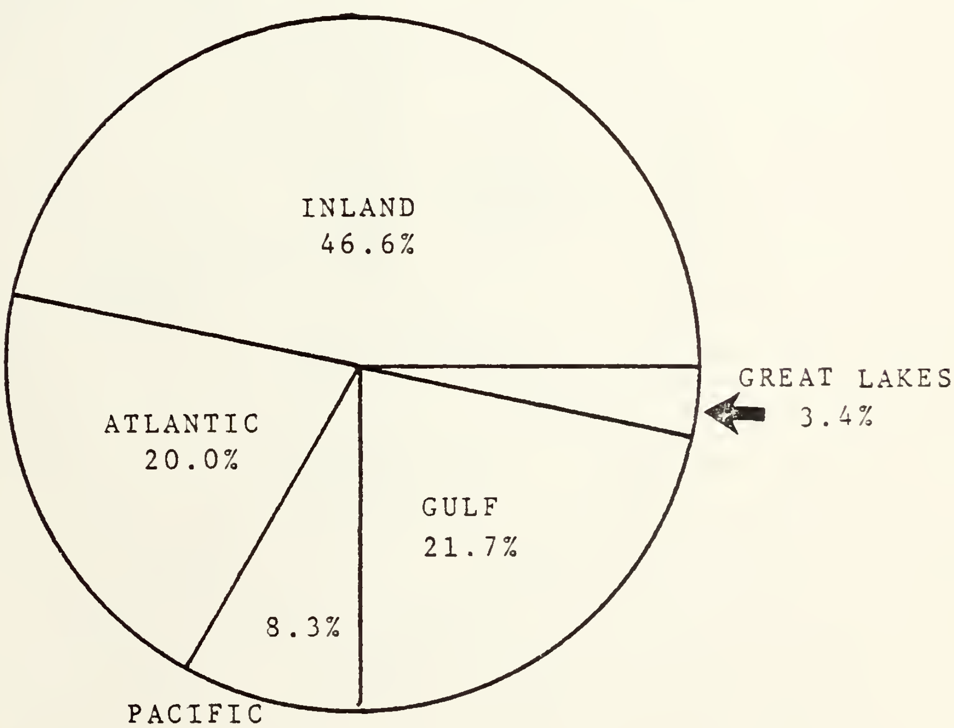
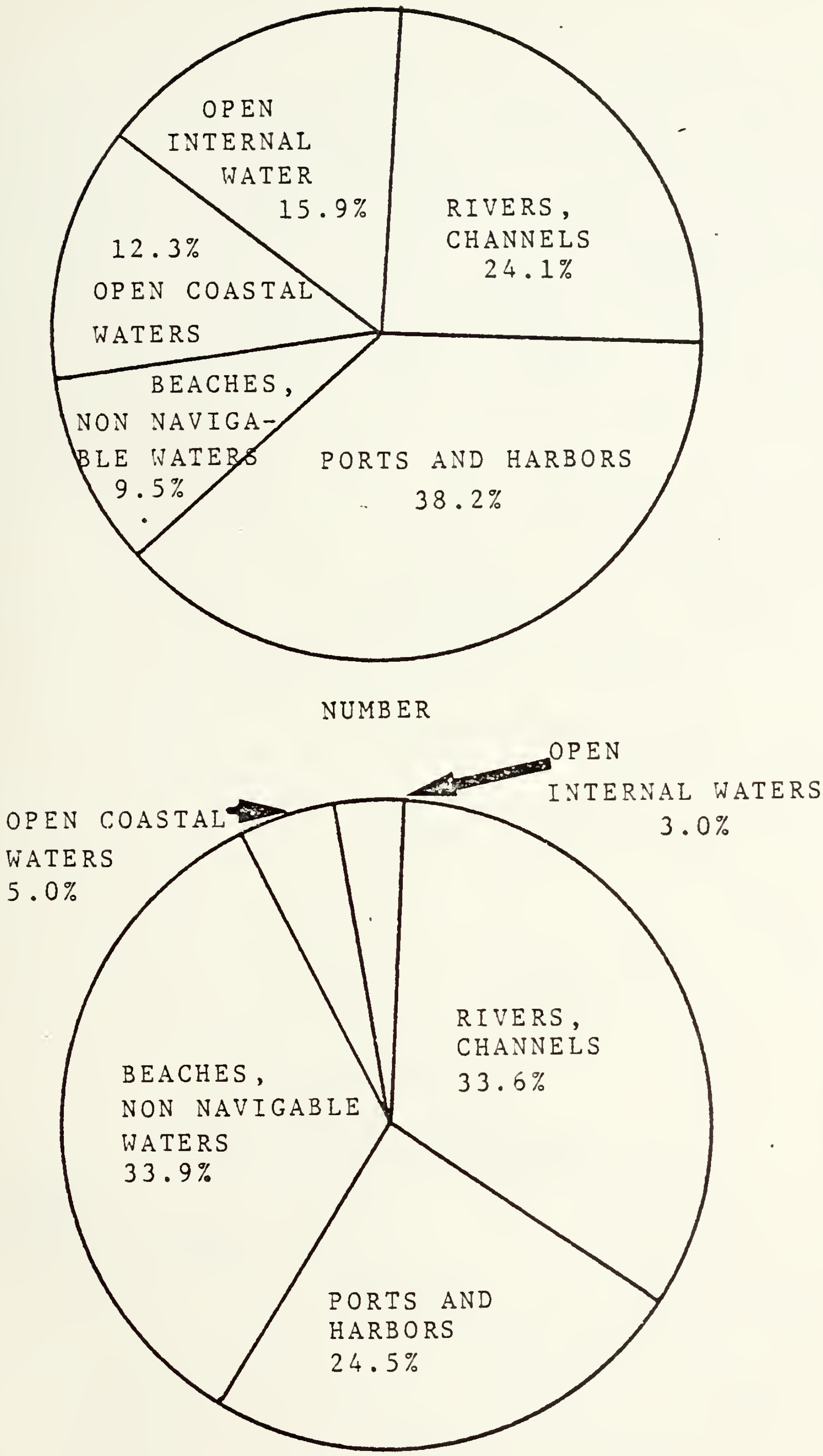


VOLUME

fig-1

Source : U.S. Coast Guard P.I.R.S. (Ref-2)

POLLUTION INCIDENTS BY LOCATION

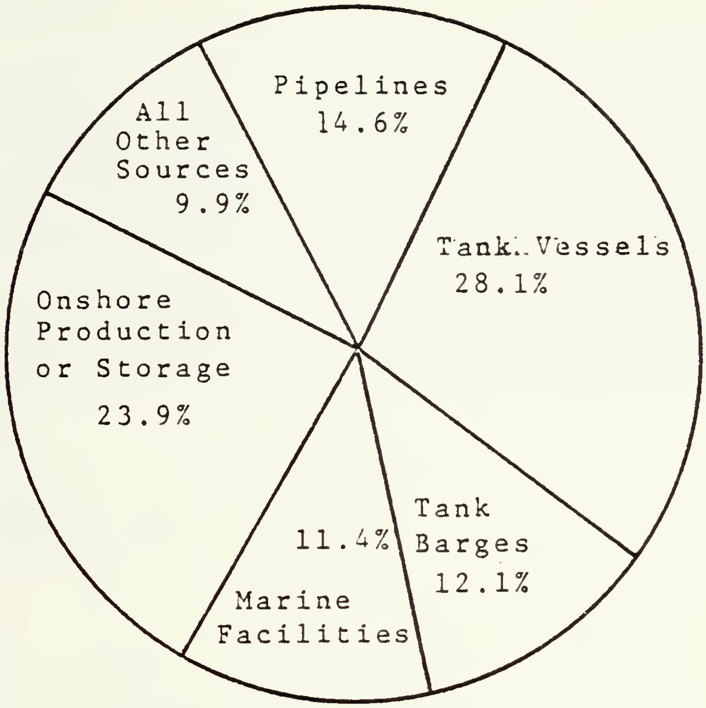


VOLUME

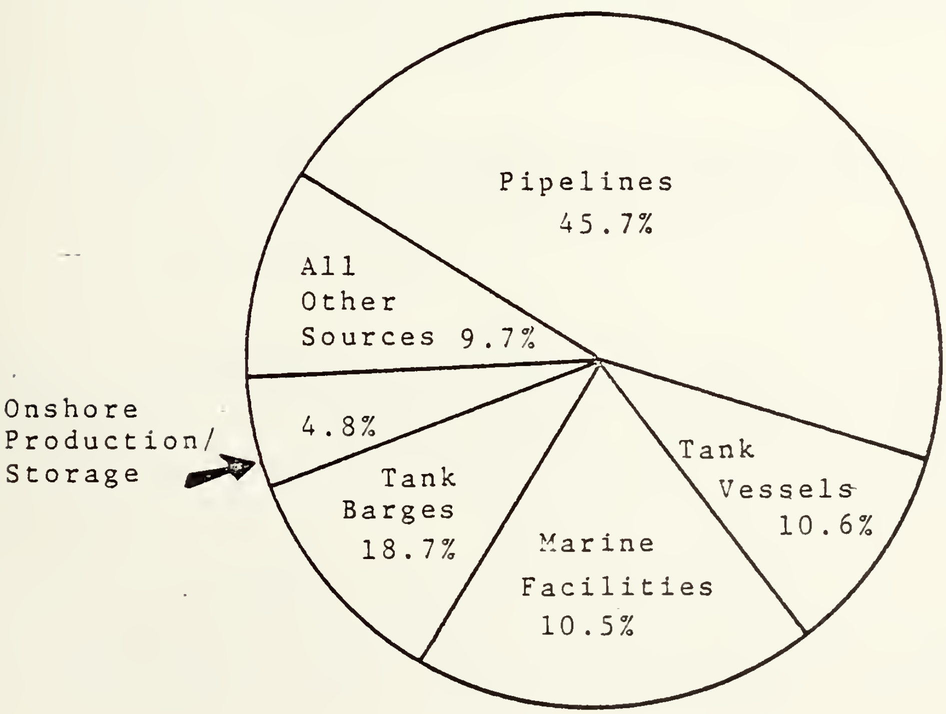
fig- 2

Source : U.S. Coast Guard P.I.R.S. (Ref-2)

SOURCES OF DISCHARGES >100,000 GALLONS



Calendar Year 1973



Calendar Year 1974

Fig-3

Source : U.S. Coast Guard P.I.R.S. (Ref-2)

B. SPILL PROBABILITY.

THE MAJORITY OF SPILLS ARE QUITE SMALL . HOWEVER, IT IS THE VOLUME OF LARGE SPILLS THAT HEAVILY INFLUENCES THE SIZE OF AVERAGE SPILLAGE.
RELIANCE ON THE ANNUAL AVERAGE VOLUME SPILLED OVER A PROJECTED TIME PERIOD CAN BE QUITE MISLEADING.
IN REALITY, THE ENVIRONMENTAL IMPACT OF OIL SPILLS DEPENDS BOTH ON THE FREQUENCY AND SIZE OF SPILLS.
IT ALSO DEPENDS ON THE RATE OF SPILL DISCHARGE RELATIVE TO THE ABILITY TO CLEAN UP THE SPILL.

BOTH DEVANNEY AND PAULSON (REF-2) CONCLUDE THAT THE OCCURENCE OF A POLLUTION INCIDENT IS ESSENTIALLY A RANDOM PROCESS AND CAN BE DESCRIBED BY A POISSON DISTRIBUTION :

$$P(N|\lambda) = e^{-\lambda X} \frac{(\lambda X)^N}{N!}$$

WHERE :

N = # OF SPILLS

X = VOLUME HANDLED

λ = MEAN SPILL INCIDENCE RATE IN # SPILLS/VOLUME HANDLED.

$P(N|\lambda)$ = PROBABILITY OF 'N' SPILLS OCCURING GIVEN λ.

THEY CONCLUDE THAT :

1. AVERAGE SPILL SIZES ARE RATHER MEANINGLESS STATISTICS SINCE THE VOLUME RANGE IS SO GREAT.

2. THE TRUE IMPACT OF SPILLS IS A FUNCTION OF FREQUENCY SIZE AND LOCATION.

BRUCE BEYAERT (REF-5) ESTIMATES THE RISK OF AN OIL SPILL BY MEANS OF A STATISTICAL PROBABILITY ANALYSIS USING THE PROCEDURE ILLUSTRATED IN FIGURE-4.
THIS ILLUSTRATION ASSUMES THAT AN ADEQUATE AND VALID BODY OF DATA IS AVAILABLE TO INDICATE THE ACTUAL NUMBER AND SIZE OF ACCIDENTAL OIL SPILLS .
THE DATA WAS USED TO DETERMINE BOTH THE PROBABILITY OF A SPILL EVENT AND ALSO THE PROBABLE DISTRIBUTION OF SPILL SIZE FOR EACH EVENT.
USING THIS ANALYSIS, THE RECURRENCE INTERVAL FOR ANY SPILL SIZE CAN BE COMPUTED FOR RANGE OF INTEREST.
THE RECURRENCE INTERVAL IS THE AVERAGE PERIOD OF TIME BETWEEN TWO SPILLS GREATER THAN OR EQUAL TO A SPECIFIED SIZE
THIS APPROACH IS EASILY UNDERSTOOD. BUT ITS USE DEPENDS ON THE VALID AND RELEVANT OIL SPILL DATA, WHICH UNFORTUNATELY IS VERY HARD TO OBTAIN IN MOST INSTANCES.

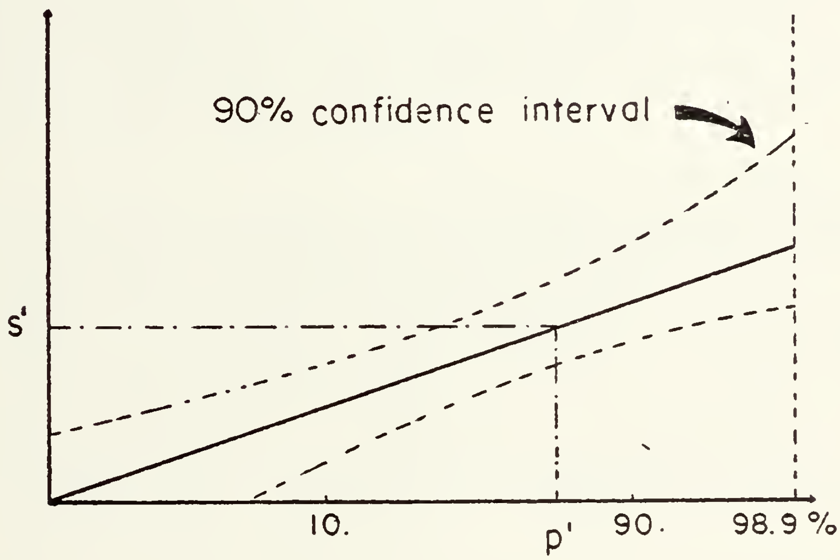
ILLUSTRATION OF AN OIL SPILL RISK ANALYSIS

1. SPILL FREQUENCY

USING VALID AND RELEVANT HISTORICAL DATA, AN ESTIMATE FOR - N - IS MADE. THIS ESTIMATION IS THE AVERAGE NUMBER OF SPILL EVENTS PER YEAR: BASED ON CORRELATION WITH AN APPROPRIATE OPERATING PARAMETER SUCH AS THE NUMBER OF TANKER PORT VISITS, THE NUMBER OF OIL TRANSFER OPERATIONS OR THE VOLUME OF OIL HANDLED.

2. SPILL SIZE DISTRIBUTION

USING VALID AND RELEVANT HISTORICAL DATA, DETERMINE THE PROBABILITY DISTRIBUTION OF ACTUAL SPILL SIZES.



P' = PERCENT PROBABILITY, THAT A SPILL WILL HAVE A SIZE LESS THAN OR EQUAL TO S', GIVEN THAT A SPILL HAS OCCURED.

3. RECURRENCE INTERVAL

FROM THE ABOVE, 'R', THE RECURRENCE INTERVAL IN YEARS CAN BE ESTIMATED FOR SPILLS OF VARIOUS SIZES BY USING THE FOLLOWING RELATIONSHIP:

$$R' = \frac{100}{N(100 - S')}$$

FIGURE-4

III. THE SPREAD OF OIL SPILLAGE IN WATER.

A. THE FATE OF OIL

IF OIL IS SPILT ON LAND, PART OF IT WILL BE ABSORBED INTO THE SOIL AND PART OF IT WILL FLOW OVER THE SURFACE SEEKING A LOW SPOT.
THE FATE OF OIL SPILLED ON THE WATER IS A VERY COMPLEX SUBJECT. MUCH EFFORT HAS BEEN MADE TO ESTIMATE THE PHYSICAL SPREADING AND MOVEMENT OF OIL ON THE SURFACE OF WATER UNDER THE INFLUENCE OF WIND, WAVES AND CURRENTS.
THE PREDICTIVE MODELS DEVELOPED SO FAR ARE NOT CAPABLE OF HANDLING SUCH COMPLEXITIES AS :

1. EVAPORATION, DISSOLUTION, SEDIMENTATION, EMULSIFICATION, ALTO/PHOTO-OXIDATION AND BIODEGRADATION.

2. THE CHANGE IN PHYSICAL AND CHEMICAL PROPERTIES OF FLOATING OIL RESULTING FROM PART ONE.

3. THE EFFECT OF SEA CONDITIONS.

IT WAS OBVIOUS FROM EXPERIMENTS & EXPERIENCES THAT SMALL QUANTITIES OF OIL, I.E. A FEW TONS (ONE TON OF OIL APPROX. EQUAL TO 6.5 BARRELS OR 250 GALLONS OR 947 LITERS) DISAPPEAR RAPIDLY FROM THE MARINE ENVIRONMENT.
THE GENERAL NATURE OF OIL DISAPPEARANCE INVOLVES SUCH PHENOMENA AS SPREADING, EVAPORATION, EMULSIFICATION, DISSOLUTION, AUTO-OXIDATION AND BIODEGRADATION (REF-10).
IT GRADUALLY DISAPPEARS THROUGH DESTRUCTIVE AND DISPERSIVE PROCESSES, LEAVING AN ASPHALTIC MASS.
OIL SINKS AFTER ITS DENSITY IS INCREASED BY EVAPORATION, BY SOLUTION OF ITS VOLATILE FRACTIONS, BY INCLUSION OF PARTICULATE MATERIAL AND BY OXIDATION (ZOBELL 1964, PILPEL 1968, REF-5). SINKING MAY HAVE BEEN OF PARTICULAR IMPORTANCE IN THE SAN FRANCISCO SPILL (REF-5).

A GREAT MANY PUBLICATIONS ON THE METABOLISM OF HYDROCARBONS IN WATER SUGGEST THAT ALL MOLECULES PRESENT IN CRUDE OIL CAN BE ATTACKED BY ENZYMES OF THE MICROORGANISMS. THIS NATURAL PROCESS, HOWEVER, MAY BE TOO SLOW UNDER NORMAL CONDITIONS AND THEREFORE, UNABLE TO CAUSE DESTRUCTION OF LARGE OIL SPILLS BEFORE DAMAGE IS DONE TO MARINE LIFE AND COASTAL AREAS.
IN THE AUTO-OXIDATION PROCESS, TEMPERATURE IS AN IMPORTANT PHYSICAL FACTOR. AT SEA, BELOW FIVE DEGREES CELCIUS, OXIDATION IS VERY SLOW, IT THUS OCCURS WITH GREAT DIFFICULTY IN LATITUDES ABOVE 75 DEGREES NORTH OR BELOW 75 DEGREES SOUTH.
IN EQUATORIAL REGIONS, THE RATE OF OXIDATION MAY ATTAIN A RATE OF SEVERAL HUNDRED GRAMS OF OIL PER CUBIC METER OF WATER PER YEAR (G.D. FLOODGATE, 'MICROBIAL DEGRADATION OF OIL', MAR.POLL BUL. 3 1972, P41-43)
OIL REMAINING AT SEA FOR THREE MONTHS OR MORE, LOSES VOLUME CONTINUALLY AND MAY BE REDUCED TO ASPHALTIC RESIDUE REPRESENTING AS LITTLE AS 15% OF THE ORIGINAL VOLUME (SMITH 1968, REF-5).

SIVADIER AND MIKOLAJ (REF-10) AFTER ASSESSING THE ROLE THAT VARIOUS FACTORS MIGHT PLAY IN DETERMINING THE FATE OF OIL SPILLS, IDENTIFIED EVAPORATION AS BEING THE MOST SIGNIFICANT. EVAPORATION IS ENCHANCED BY INCREASING WIND SPEED, SEA SURFACE ROUGHNESS, AIR TEMPERATURE AND DECREASING OIL FILM THICKNESS. LIGHTER WEIGHT OIL EVAPORATES FASTER THAN HEAVIER TYPES.

B. MODEL OF DISAPPEARANCE OF OIL SPILLS DUE TO EVAPORATION.

TWO BASIC ASSUMPTIONS MADE BY SIVADIER AND MIKOLAJ IN THEIR MODEL :

1. APART FROM SPREADING, THE ONLY PROCESS OCCURING TO ANY APPRECIABLE EXTENT IS EVAPORATION. IN OTHER WORDS, DISSOLUTION, AUTO-OXIDATION AND BIO-DEGRADATION ARE CONSIDERED NEGLIGIBLE.

2. OIL CONSISTS OF TWO ARBITRARY DEFINED PARTS :

   A. A VOLATILE FRACTION FROM WHICH ALL EVAPORATIVE LOSSES OCCUR

   B. A RESIDUUM FRACTION WHICH IS TOTALLY UNAFFECTED BY WEATHERING.

F = C1*T/(1 + C2*T)

WHERE:

F = THE WEIGHT FRACTION OF THE WEATHERED OIL SAMPLE WHICH IS EVAPORATED, IN PERCENT.

C1,C2 = CONSTANT, IN WHICH THE VALUE DEPENDS ON THE TYPE OF OIL, WEATHER AND WATER CONDITION.

T = TIME, IN MINUTES.

AS TIME APPROACHES INFINITY, THE VALUE OF 'F' CONVERGES TO 20 - 22% (REF-10).

SINCE THE REMAINING OIL SLICK RESIDUE WOULD HAVE A SPECIFIC GRAVITY NEARLY THE SAME AS SEA WATER, THERE IS CONSIDERABLE LIKELIHOOD THAT THIS OIL SLICK RESIDUE COULD ENTER THE WATER COLUMN WHERE IT WOULD THEN BE SUBJECT TO SUBSURFACE TRANS-PORT MECHANISM.

C. MODEL TO DETERMINE THE LEEWAY OF OIL SLICKS.

THE MOVEMENT OF SPILLED OIL ON THE SEA IS MAINLY DEPEND-ENT ON THE CURRENT VELOCITY OF THE WATER SUPPORTING THE OIL SLICK AND THE VELOCITY OF THE LOCAL WIND. LEEWAY IS DEFINED AS THE MOVEMENT OF OIL SLICK OVER THE WATER DUE TO THE ACTION OF THE WIND.

SMITH (REF-4) CONCLUDE THAT :

1. ALL LIGHT AND HEAVY CRUDE OIL, EXHIBIT POSITIVE LEEWAY AS A FUNCTION OF WIND SPEED. DIFFERENCES BETWEEN OIL TYPES WERE NOT FOUND TO BE SIGNIFICANT AND SHOWED NO CORRELATION WITH PHYSICAL CHARACTERISTICS OF THE OIL.

2. OIL SLICK LEEWAY FOR ALL OIL TYPES IN THE WIND RANGE FROM 5 - 25 KNOTS MAY BE CALCULATED FROM THE EXPRESS-ION :

OSL = 0.0179*W10 + 0.0196

WHERE:

OSL = OIL SLICK LEEWAY, IN KNOTS.

W10 = WIND SPEED AT 10 METERS ELEVATION, IN KNOTS.

3. THE EXPRESSION FOR WIND IN RANGE LESS THAN FIVE KNOTS SHOULD USE:

OSL = 0.0199*W10.

4. OIL SLICKS MOVE IN THE DIRECTION OF WIND ACROSS THE WATER SURFACE.

5. OIL SPILL VOLUME WAS NOT FOUND TO AFFECT THE MAGNITUDE OF THE SLICK LEEWAY, BUT VERY THIN OIL FILMS WERE FOUND TO EXHIBIT LITTLE OR NO LEEWAY.

6. OIL SLICK LEEWAY INCREASES AS A POSITIVE FUNCTION OF SEA STATE, BUT THE RELATIONSHIP WAS NOT QUANTITATIVELY DEFINED.

7. OIL SLICK MOVES ACROSS THE WATER SURFACE UNDER THE INFLUENCE OF THE WIND LEAVING A THIN FILM ALONG THEIR PATH.

C. OIL SLICK SPREADING ANALYSIS.

IT IS A COMMON OBSERVATION THAT OIL, WHEN SPILLED ON WATER TENDS TO SPREAD OUTWARD ON THE WATER SURFACE IN THE FORM OF A THIN LAYER. THIS TENDENCY TO SPREAD IS THE RESULT OF TWO PHYSICAL FORCES: THE FORCE OF GRAVITY WHICH CAUSES THE LIGHTER OIL TO SEEK A CONSTANT LEVEL BY SPREADING HORIZONTALLY, JUST AS IT WOULD ON A PLANE HORIZONTAL SOLID SURFACE AND THE SURFACE TENSION FORCE OF PURE WATER, WHICH IS USUALLY GREATER THAN THAT OF THE OIL FILM FLOATING ON WATER.
IN THE OPEN SEA, THIS SPREADING TENDENCY IS AIDED BY WATER SURFACE MOTIONS INDUCED BY WAVES, WIND AND TIDAL CURRENTS. THESE EXTERNAL FORCES MAY BE THE ONLY CAUSE OF SPREAD IF THE SLICK HAS BEEN BROKEN INTO SMALL INDEPENDENT PIECES. THE SPREAD RESULTING FROM THIS RAMDOM MOTION OF THE SEA SURFACE IS VERY DIFFICULT TO ESTIMATE. MOST OILS SPILLED ARE MIXTURES OF COMPONENTS HAVING VARYING VAPOR PRESSURE AND SOLUBILITY IN WATER. THE LIGHTER MOLECULAR WEIGHT ARE MORE VOLATILE AND SOLUBLE, AND THE HEAVIER/RESIDUE IS DENSER AND MORE VISCOUS.

FAY (REF-6,10) HAS DEVELOPED AN ANALYSIS FOR THE SPREADING OF A ONE DIMENSIONAL AND AXISYMETRIC OIL SLICK AS A FUNCTION OF TIME. THE ANALYSIS IS RESTRICTED TO A FIXED AMOUNT OF OIL IN THE INITIAL SPILL AND THE WATER IS FREE OF MOTION INDUCED BY WIND, WAVES AND TIDAL CURRENTS.
THE SPREADING PROCESS PROCEEDS THROUGH THREE STAGES IN WHICH VARIOUS FORCE PAIRS ARE IMPORTANT AND THE SLICK FINALLY REACHES A TERMINAL SIZE. FOR THE AXI-SYMETRIC CASE, THE RADIUS OF THE SLICK 'R' IS RELATED TO TIME AFTER THE SPILL BEGINS, 'T', BY THE FOLLOWING EQUATIONS:

GRAVITY-INERTIA STAGE:

$$R_1 = (\Delta \cdot G V T^2)^{1/4} \cdot C_1$$

GRAVITY-VISCOUS STAGE:

$$R_2 = \left(\frac{\Delta G V^2 T^{3/2}}{\nu_\omega}\right)^{1/6} \cdot C_2$$

SURFACE TENSION-VISCOUS STAGE:

$$R_3 = \left(\frac{\sigma^2 T^3}{\rho_\omega^2 \nu_\omega}\right)^{1/4} \cdot C_3$$

WHERE:

C1 = 1.14

C2 = 1.45

C3 = 2.30

G = GRAVITY, GR/CM**2

Δ = $(\rho_\omega - \rho_0)/\rho_\omega$

ρ_ω = WATER DENSITY, GR/CM**3

ρ_0 = OIL DENSITY, GR/CM**3

V = VOLUME, CM**3

σ = SPREADING COEFFICIENT, DYNE/CM

ν_ω = WATER KINEMATIC VISCOSITY, CM**2/SEC.

T = TIME, SECOND.

R = RADIUS, CM

THE FINAL RADIUS OF THE SPILL :

$$R_f = \left(\frac{10^5 V^{3/4}}{\Pi}\right)^{1/2}$$

WHERE:

RF = RADIUS, METER.

V = VOLUME, M^3

THE TIME AT WHICH THE TRANSITION FROM THE INERTIA STAGE TO THE VISCOUS STAGE OCCURS, 'T12', CAN BE FOUND BY EQUATING FROM THE SPILL RADII FROM EQUATION 'R1' AND 'R2'.

$$T_{12} = \left(\frac{C_2}{C_1}\right)^4 \left(\frac{V}{\Delta G \nu_\omega}\right)^{1/3}$$

SIMILARLY FOR THE VISCOUS-SURFACE TENSION TRANSITION TIME:

$$T_{23} = \left(\frac{C_2}{C_3}\right)^2 \left(\frac{\rho_\omega}{\sigma}\right) \left(\Delta G \nu_\omega\right)^{1/3} \cdot V^{2/3}$$

IN THIS STUDY THE FOLLOWING VALUES ARE USED :

$G = 980\ CM/SEC^2$

$\sigma = 10$ DYNE/CM

$\rho_\omega = 1.0$

$\rho_o = 0.95$

LATITUDE = 38 DEGREE NORTH

$\nu_\omega = 0.01\ CM^2/SEC.$

D. MOVEMENT OF SPILLED OIL IN SAN FRANCISCO BAY AREA.

THE INTENT OF THIS STUDY IS TO PRESENT DESCRIPTIONS OF GENERAL SURFACE WATER MOVEMENTS IN THE SAN FRANCISCO BAY AREA AND ITS IMPACT ON THE DISTRIBUTION AND DISPERSAL OF OIL SPILLS IN THE BAY.
A SIMULATION METHOD IS USED TO PREDICT THE DISPERSAL OF SPILLED OIL.
THE SAN FRANCISCO BAY SYSTEM CAN BE DIVIDED INTO A NORTH BAY - CENTRAL BAY AND A SOUTH BAY.
PERRENIAL ESTUARINE CIRCULATION IN THE NORTH AND CENTRAL BAY AND THE ADJACENT OCEAN IS MAINTAINED BY THE SACRAMENTO - SAN JOAQUIN RIVER RUN OFF. ANNUALLY THE AVERAGE SURFACE SEAWARD DRIFT EXCEEDS FIVE KM PER DAY (REF-5).
WIND IS A MAJOR FACTOR IN DETERMINING CIRCULATION IN THE SOUTH BAY. LOCAL WINDS ARE TOPOGRAPHICALLY CONTROLLED BY PREDOMINANTLY NORTHWEST WINDS DURING SUMMER AND THE SOUTH EAST WINDS DURING WINTER STORMS, WITH THE PREVAILING SUMMER WIND GENERALLY TWICE AS STRONG AS THAT IN WINTER (REF-5).
THE SOUTH BAY CIRCULATION IS RELATIVELY SLUGGISH. THE ANNUAL AVERAGE SPEED OF SURFACE DRIFT, REGARDLESS OF DIRECTION IS BETWEEN ONE AND TWO KM PER DAY. THE MOVEMENTS OF SURFACE DRIFTERS IN SAN FRANCISCO BAY ARE SHOWN IN FIGURE-5 (REF-5).
AN EXAMPLE OF THE SPREAD AND THE MOVEMENT OF OIL SLICKS PLOTTED BY THE COMPUTER SIMULATION IS SHOWN IN FIGURE-6.

ANALYSIS OF OIL SPILL MOVEMENT
IN SAN FRANCISCO BAY AREA
AS PREDICTED BY ESTUARINE NON TIDAL DRIFT

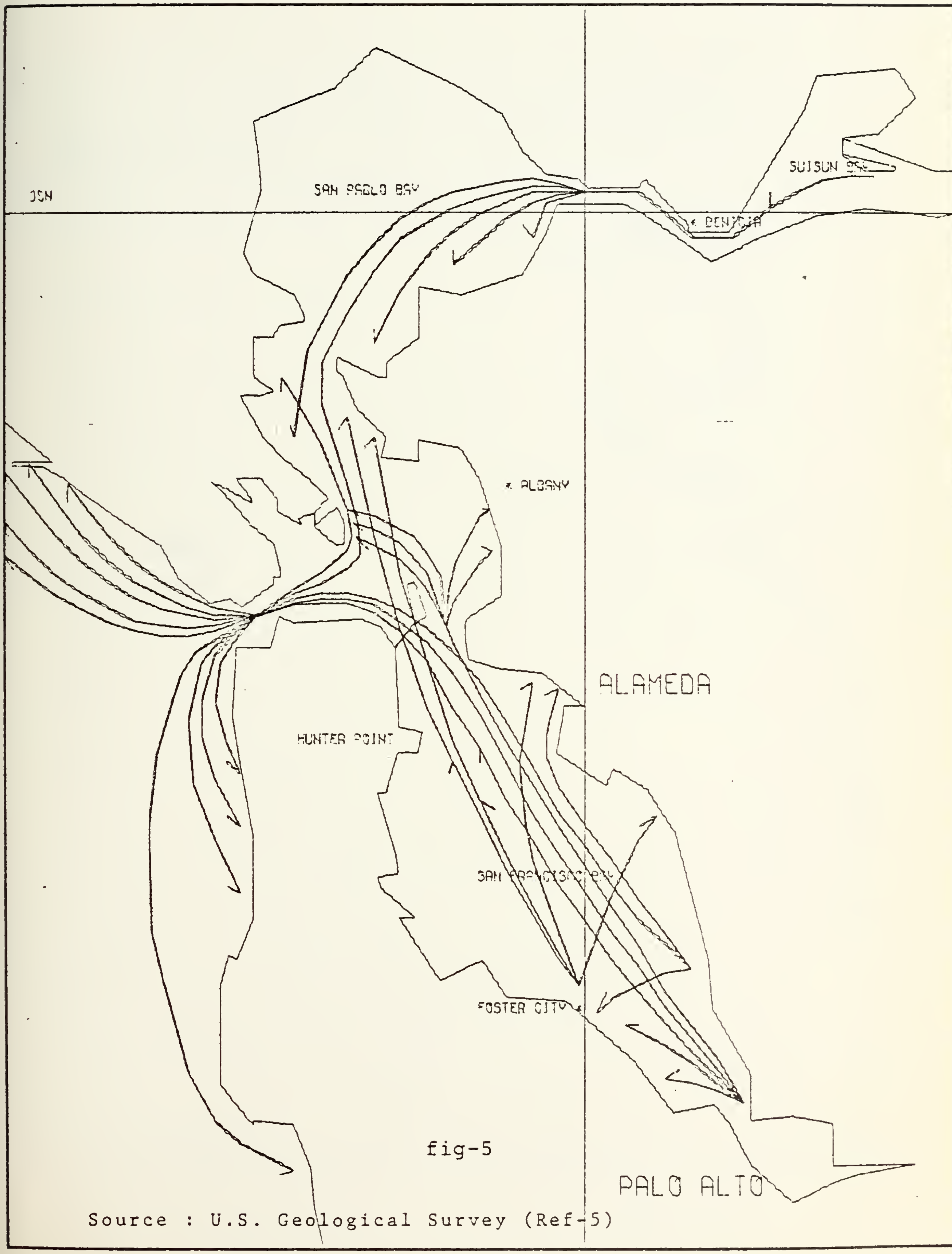


fig-5

Source : U.S. Geological Survey (Ref-5)

WEST SOUTHERN BAY

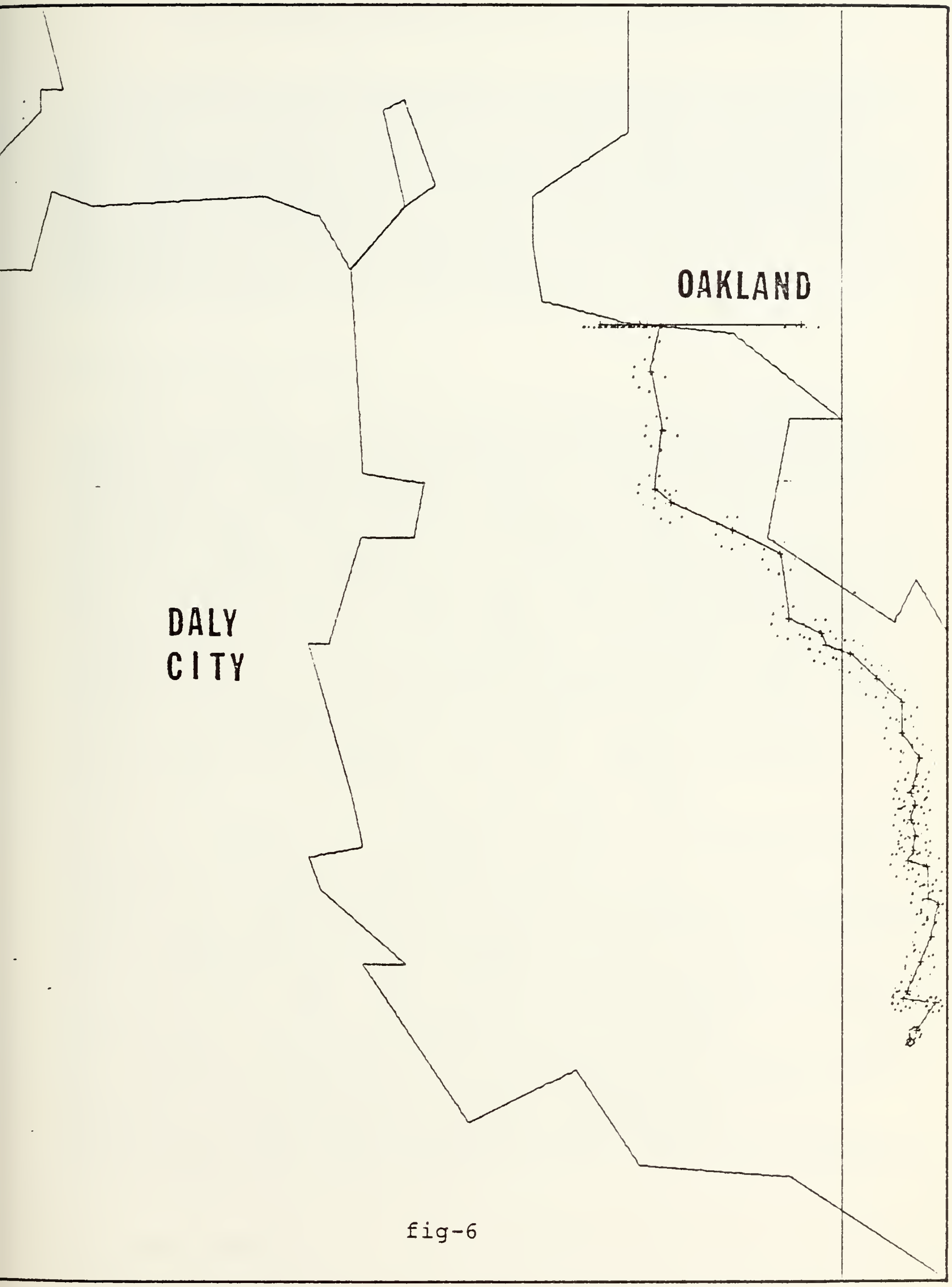


fig-6

IV. FACTORS AFFECTED BY THE OIL POLLUTION.

CRUDE OIL AND OIL PRODUCTS SPILLED IN NATURE ARE ALTERED BY EVAPORATION, BY DISSOLUTION, BY BACTERIAL AND CHEMICAL ATTACK.
IN SPITE OF COMPLEX PROCESSES OCCURING DURING WEATHERING, MANY COMPOSITIONAL PARAMETERS ARE RELATIVELY STABLE AND ARE NOT OBLITERATED UNTIL AN ADVANCED STAGE OF DEGRADATION HAS BEEN REACHED (REF-1).
THE STABLE PARAMETERS MAY AID THE IDENTIFICATION OF AN OIL POLLUTANT AND IN THE CORRELATION WITH ITS SOURCE FOR MANY WEEKS AFTER THE SPILL (REF-1,2).
THE EFFECTS OF OIL POLLUTION CAN BE DIVIDED INTO TWO GROUPS, MECHANICAL DAMAGE AND TOXIC EFFECTS.

A. MECHANICAL DAMAGE.

A MOST OBVIOUS EFFECT OF AN OIL SPILL IS THE AROUSED CITIZEN INTEREST WHEN NEARBY RESOURCES ARE POLLUTED BY THE SPILL. THE VISIBLE RESULT MAY BE AN OILED BEACH WHICH HAS BECOME LESS ATTRACTIVE,DISCOURAGING SWIMMING AND FISHING. ALTHOUGH OIL COATED BEACHES CAN BE CLEANED COSMETICALLY, THEY CANNOT BE DISINFECTED (REF-2).
IF LARGE QUANTITIES ARE SPILLED,THESE EFFECTS CAN BE IMPORTANT. SEA BIRDS ARE PERHAPS THE MOST OBVIOUS SUFFERERS. THEY DIE WHEN OIL DESTROYS THE NATURAL INSULATING QUALITIES OF THEIR FEATHERS (REF-8) OR MAKES FLIGHT IMPOSSIBLE, RESULTING IN DEATH BY STARVATION. DUCKS WERE FOUND TO PREEN ABOUT HALF THE POLLUTING OIL FROM THEIR FEATHERS WITHIN A WEEK, MOSTLY ON THE FIRST DAY OF OILING . LATER EXPERIMENTS (HARTUNG R. AND HUNT, G.S.J WILDE. MGMT, 1966, P564-570) SHOWED THAT THE INGESTION OF ONE THIRD TO HALF THE AVERAGE QUANTITY OF OIL EXTRACTED FROM THE PLUMAGE OF BIRDS FOUND DEAD FROM MODERATE OILING, PRODUCES SERIOUS INTERNAL EFFECTS. BUT THE IMMEDIATE CAUSE OF DEATH IN A BIRD OILED AT SEA IS EXPOSURE OR DROWNING.
IN ADDITION, OIL DISRUPTS THE BIRDS' NESTING GROUNDS. ASIDE FROM BIRDS, SIGNIFICANT IMPACT DOES NOT GENERALLY OCCUR UNTIL OIL REACHES THE INTERTIDAL ZONE.

THE MOST ECOLOGICALLY IMPORTANT IMPACT COULD OCCUR ON THE SHORE OF MARSHES AND ESTUARIES WHICH HAVE EXTREMELY HIGH BIOLOGICAL PRODUCTIVITY (REF-1,2,7).
SMOTHERING OF SHORE CRABS AND SESSILE INVERTIBRATES (NON COMMERCIAL WATER ANIMALS) CAN OCCUR IN THE UPPER INTERTIDAL ZONE OF THE OPEN COAST,BUT ARE OF CONSIDERABLY LESS ECOLOGICAL SIGNIFICANCE (BRUCE BEYAERT, ANALYSIS OF OIL ACCIDENTS FOR ENVIRONMENTAL IMPACT STATEMENT, REF-1 P 43).
ON THE SHORE ITSELF MOST SEAWEEDS HAVE AN OUTER LAYER TO WHICH OIL DOES NOT CLING, SO MODERATE QUANTITIES OF OIL CANNOT DO MUCH DAMAGE. INDIRECTLY IT CAUSES DAMAGE TO OTHER SPECIES WHICH DEPEND ON THESE PLANTS AS FOOD.
A HEAVY SPILL WILL BLANKET EVERYTHING ON THE SHORE AND CLOG THE GRASSES AND REEDS OF SALT-MARSHES,PARTICULARLY IF THE OIL HAS BECOME EMULSIFIED. A HEAVY RESIDUE OF CRUDE OIL REDUCED THE POPULATION OF WINKLES (LARGE SEA SNAILS) ALTHOUGH THE RESIDUE WAS VIRTUALLY NON TOXIC.
A COATING OF OIL,EITHER ON THE SURFACE OF WATER OR ON AN INDIVIDUAL PLANT,ALSO INTERFERES WITH LIGHT PENETRATION AND THUS PHOTO-SYNTHESIS (REF-7).

B. TOXIC EFFECTS.

THE PHYTOTOXIC EFFECT OF HYDROCARBONS HAD BEEN STUDIED

IN MOST DETAIL ON TERRESTRIAL PLANTS . IT WAS FOUND THAT TOXICITY IN SMALLER MOLECULES WAS GREATER THAN IN LARGER ONES.
FISH USUALLY KEEP WELL CLEAR OF AN OIL SPILL IF THEY CAN. SHELLFISH ARE AFFECTED BY OIL DUE TO THEIR LACK OF MOBILITY. FIVE TO TEN PERCENT CRUDE OIL SLOWS THE PUMPING RATE OF OYSTERS THUS AFFECTING THEIR FEEDING, RESPIRATION AND GENERAL CONDITION (REF-7).
THIS HAS MEANT FINANCIAL LOSSES FOR FISHERMEN AND PROCESSORS . ALSO, SOME COMMERCIAL SPECIES CAN ACCUMULATE POTENTIALLY CARCENOGENIC SUBSTANCES, DAMAGING THE ORGANISM ITSELF OR MAKING IT UNFIT FOR CONSUMPTION BY MAN AND OTHER ANIMALS. AQUATIC LIFE UNDER CONDITIONS OF LONG TERM OR CONTINUOUS EXPOSURE TO OIL SPILLS DEVELOPES SUBTLE CHANGES IN THE BEHAVIOR PATTERN SUCH AS LOSING THEIR ABILITY TO SECURE FOOD, AVOID INJURY, ESCAPE FROM ENEMIES, CHOOSE A HABITAT, RECOGNIZE TERRITORY, MIGRATE, COMMUNICATE AND REPRODUCE (REF-8) .

C. IMPACT OF A DISCHARGE.

AN OIL SPILL CAN HAVE ADVERSE SOCIAL,ECONOMIC AND ENVIRONMENTAL IMPACT . THE SEVERITY OF THE IMPACT DEPENDS ON THE ENVIRONMENTAL SETTING OF THE AFFECTED AREA,THE TYPE AND AMOUNT OF OIL SPILT, AND THE MITIGATION MEASURES EMPLOYED.
SOCIO-ECONOMIC IMPACTS COULD INCLUDE ADVERSE PUBLICITY AND PUBLIC CONCERN WHICH COULD TEMPORARILY DETER COASTAL RECREATION AND TOURISM.
PERSONAL PROPERTIES SUCH AS BOATS AND FISHING GEAR COULD BE FOULED BY OIL.
COMMERCIAL AND SPORT FISHING ACTIVITY COULD BE TEMPORARILY STOPPED OR CURTAILED IN THE AREA.
THE POSSIBLE IMPACTS OF A DISCHARGE CAN INCLUDE (REF-2) :

A. HAZARD TO HUMANS THROUGH EATING CONTAMINATED SEAFOOD,

B. DECREASE OF FISHERY RESOURCES, AND DAMAGE TO WILDLIFE SUCH AS SEA BIRDS AND MARINE MAMMALS,

C. DECREASE OF AESTHETIC VALUE DUE TO UNSIGHTLY SLICKS OR OILED BEACH, DECREASING THE VALUE OF PRIVATE PROPERTIES AND RECREATIONAL ACTIVITIES AND TOURISM,

D. DECREASE IN DIVERSITY AND PRODUCTIVITY OF SPECIES IN THE POLLUTED AREA.

E. MODIFICATION OF HABITATS,DELAYING OR PREVENTING RECOLONIZATION.

V. THE ECONOMICS OF OIL SPILLS

IN MARCH 1967 THE OIL TANKER TORREY CANYON FOUNDERED OFF THE SOUTHERN COAST OF ENGLAND, SPILLING 119,000 TONS OF CRUDE OIL. THE OIL SLICK QUICKLY SPREAD ACROSS NEARBY WATERS AND FOULED LARGE AREA OF ADJOINING ENGLISH AND FRENCH COASTS. THE BRITISH GOVERMMENT ALONE SPENT $8 MILLION (REF-12) ON CLEAN UP. THAT WAS ONLY A PORTION OF TOTAL CLEAN UP COSTS. IN ADDITION, THERE WAS EXTENSIVE LOSS OF MARINE LIFE AND FOULING OF BEACHES AND COASTLINES.

SINCE OIL IS NOT COMPLETELY BIODEGRADABLE OR DOES NOT DETERIORATE RAPIDLY, SLICKS AND GLOBULES OF OIL ARE VISIBLE THROUGHOUT THE HIGH SEA OF THE WORLD. THE EXACT BIOLOGICAL CONSEQUENCES ARE STILL UNDETERMINED.

IT IS TEMPTING FOR PEOPLE TO ASSERT THAT ALL POLLUTION SHOULD BE STOPPED, BUT THE SOCIETY WILL HAVE LESS REAL INCOME IF THE COSTS OF TOTAL ELIMINATION OF POLLUTION EXCEED THE BENEFITS.
FROM THIS POINT OF VIEW SOME LEVEL OF OIL POLLUTION MAY INDEED BE SOCIALLY DESIRABLE.
IT IS CRITICAL TO DEVELOP A PROCEDURE AND METHODOLOGY TO DETERMINE THE SOCIAL COST OF AN OIL SPILL SO AS TO CONDUCT PRODUCTIVE INQUIRES IN DERIVING THE SOCIALLY OPTIMAL LEVEL OF OIL SPILLAGES. THIS SECTION AS WELL AS THE FOLLOWING SECTION ARE DEVOTED TO SUCH DEVELOPMENT.

IF A SPILL OCCURS, THE DIRECT LOSS OF A PRODUCT TO THE ECONOMY MAY BE MEASURED IN TERMS OF THE MARKET VALUE OF THE PRODUCT.
THE INDIRECT COST ASSOCIATED WITH THE ENVIRONMENTAL DAMAGE IS MUCH MORE COMPLICATED.
THE INDIRECT COST IS THE FUNCTION OF SIZE, FREQUENCY, LOCATION AND TYPE OF OIL SPILLED INTO THE WATERS.

THE SOCIAL COST IS DEFINED AS VALUATION OF LOSSES IN REAL GOODS AND SERVICES RESULTING FROM THE OIL SPILL.

IN THE ABSENCE OF ANY CLEAN UP PROCEDURES (DETECTION, CHEMICALS EQUIPMENT ETC), THE SOCIAL COST OF A SPILL COULD BE DEFINED AS THE SUM OF DIRECT AND INDIRECT COSTS.

$$C(S) = A(S) + B(S)$$

WHERE:

A, THE DIRECT COST IS A FUNCTION OF SPILL SIZE AND

B, THE INDIRECT COST IS THE FUNCTION OF SIZE, FREQUENCY , LOCATION AND TYPE OF OIL.
TYPE OF OIL CHARACTERIZED THE TOXICITY TO MARINE LIFE.

A. GENERAL ECONOMIC ANALYSIS

ASSUME THAT THERE ARE N COMMODITIES IN THE ECONOMY WHICH CAN SERVE AS GOODS WHERE THE COMMODITIES ARE DEFINED FOR A PARTICULAR DATE AND PLACE SO THAT A SINGLE PHYSICAL COMMODITY DELIVERED AT TWO DIFFERENT DATES OR TWO DIFFERENT PLACES WOULD BE CONSIDERED DIFFERENT ECONOMIC COMMODITIES. ASSUME N IS FINITE, AND THE QUANTITIES OF ANY COMMODITY ARE ASSUMED PERFECTLY DIVISIBLE.
A PARTICULAR BUNDLE OF COMMODITIES IS SUMMARIZED BY THE COLUMN VECTOR 'X':

$$\bar{X} = (X_1, X_2, \ldots, X_N)'$$

THIS VECTOR IS DEFINED ON EUCLIDEAN N-SPACE, E^N, REFERED TO AS COMMODITY SPACE.
PRICE IN THE ECONOMY ARE SUMMARIZED BY ROW VECTOR $\bar{P}$:

$$\bar{P} = (P_1, P_2, \ldots, P_N)$$

PRICE ARE NON NEGATIVE AND AT LEAST ONE PRICE IS NON ZERO. THE PRICE CAN BE NORMALIZED AND ONE POSSIBLE NORMALIZATION IS THAT OF MEASURING PRICES SO THAT THEY SUM TO UNITY.

$$\sum_{j=1}^{N} P_j = 1$$

EACH OF THE FIRMS IN THE ECONOMY MUST SELECT LEVELS OF INPUTS AND OUTPUTS SUBJECT TO THE AVAILABLE TECHNOLOGY, SO AS TO MAXIMIZE PROFITS. FOR EXAMPLE THE FIRM f MAY CHOOSE INPUT-OUTPUT VECTOR $\bar{Y}^f$ IN THE COMMODITY SPACE :

$$\bar{Y}^f = (Y_1^f, Y_2^f, \ldots, Y_N^f)'$$

THE PRODUCTION POSSIBILITIES SET $\bar{T}^f$, A SUBSET OF COMMODITY SPACE IN WHICH:

$$\bar{Y}^f \in \bar{T}^f \qquad f = 1, 2, \ldots, F$$

IT IS ASSUMED THAT EACH PRODUCTION POSSIBILITIES SET IS INDEPENDENT OF THE INPUT/OUTPUT VECTOR CHOSEN BY OTHER FIRMS AND OF THE CONSUMPTION CHOICES OF CONSUMERS.

THE ECONOMY -WIDE I-O VECTOR $\bar{Y}$, IS OBTAINED BY SUMMING ALL INDIVIDUAL FIRM I-O VECTORS:

$$\bar{Y} = \sum_{f=1}^{F} \bar{Y}^f = (\sum_{f=1}^{F} Y_1^f, \ldots, \sum_{f=1}^{F} Y_N^f)$$

BY SUMMATION, INTERMEDIATE GOODS CANCEL OUT, SO ONLY FINAL OUTPUTS (MEASURED AS POSITIVE) AND PRIMARY RESOURCES (MEASURED AS NEGATIVE) APPEAR IN $\bar{Y}$.

THE ECONOMY-WIDE PRODUCTION POSSIBILITIES SET $\bar{T}$ IS OBTAINED BY SUMMING ALL FIRM PRODUCTION POSSIBILITIES SETS :

$$\bar{Y} \in \bar{T} = \sum_{f=1}^{F} \bar{T}^f$$

ASSUMPTIONS :

1. $\bar{T}$ IS CONVEX: $\bar{Y},\bar{Z} \longrightarrow \alpha\bar{Y} + (1-\alpha)\bar{Z} \in \bar{T} \quad 0 \leq \alpha \leq 1$
2. IT IS IMPOSSIBLE TO PRODUCE OUTPUTS USING NO INPUTS.
3. OUTPUT AND INPUT CANNOT BE REVERSED.
4. IT IS POSSIBLE TO USE INPUTS AND PRODUCE NO OUTPUT. INPUTS BEING FREELY DISPOSABLE.

SINCE OUTPUTS ARE MEASURED AS POSITIVE AND INPUTS AS NEGATIVE, THE PROFIT OF FIRM f :

$$\Pi^f = \bar{P}.\bar{Y}^f = \sum_{j=1}^{N} P_j \, . Y_j^f$$

TOTAL PROFIT Π IS MAXIMIZED WITHIN $\bar{T}$ IFF ALL FIRMS MAXIMIZE THEIR INDIVIDUAL PROFITS Π^f WITHIN THEIR PRODUCTION POSSIBILITIES SETS $\bar{T}^f$.

EACH OF THE CONSUMER H IN THE ECONOMY MUST SELECT LEVELS OF PURCHASES SUBJECT TO A BUDGET CONSTRAINT.

CONSUMER h SELECTS A CONSUMPTION VECTOR $\bar{C}^h$:

$$\bar{C}^h = (C_1^h , C_2^h , \dots , C_N^h)' \quad E^N$$

THE TASTE OF CONSUMERS ARE SUMMARIZED BY THE PREFERENCE RELATION, ASSUMED CONVEX AND CONTINUOUS. ALSO ASSUMED THAT THE PREFERENCE RELATION FOR ANY CONSUMERS IS INDEPENDENT OF THE CONSUMPTION CHOICES OF OTHER CONSUMERS.

THE BUDGET CONSTRAINT B :

$$B = \bar{P}.\bar{C}^h = \sum_{j=1}^{N} P_j \, . C_j^h$$

TOTAL CONSUMPTION LEVELS FOR THE ECONOMY $\bar{C}$,IS OBTAINED BY SUMMING ALL INDIVIDUAL CONSUMER CONSUMPTION VECTORS :

$$\bar{C} = \sum_{h=1}^{H} \bar{C}^h$$

IF $\bar{A}$ REPRESENT TOTAL RESOURCES FOR THE ECONOMY, THEN WEALTH OF THE ECONOMY W :

$$W = \bar{P}.\bar{A}$$

A COMPETITIVE EQUILIBRIUM IS DEFINED AS A SITUATION IN WHICH PRICE VECTOR SATISFIES :

1. $\Phi_i(P^*) \leqslant 0 \qquad i = 1,2,\ldots,N$

(non positive excess demand function)

2 $P_i^* \Phi_i(P^*) = 0 \qquad i = 1,2,\ldots,N$

THE PROFIT MAXIMIZING I-O VECTOR OF EACH FIRM IS SUMMARIZED

$$\bar{Y}^* = (\bar{Y}^{1*}, \bar{Y}^{2*}, \ldots, \bar{Y}^{F*})$$

THE EQUILIBRIUM CONSUMPTION VECTOR OF EACH CONSUMER :

$$\bar{C}^* = (\bar{C}^{1*}, \bar{C}^{2*}, \ldots, \bar{C}^{H*})$$

PROFIT MAXIMIZING SUBJECT TO THE AVAILABLE TECHNOLOGY AND POLLUTION LEVEL :

$$= \bar{P}^* \cdot \bar{Y}^{f*} > \bar{P}^* \cdot \bar{Y}^{f} \quad \text{FOR ALL} \quad \bar{Y}^{f} \in \bar{T}$$

A PARETO OPTIMUM IS A SET OF CONSUMPTION VECTORS :

$$(\bar{C}^{1*}, \bar{C}^{2*}, \ldots, \bar{C}^{H*})$$

WHICH IS CONSISTENT WITH THE TECHNOLOGY AND BUDGET AND FOR WHICH THERE EXISTS NO OTHER SET OF CONSUMPTION VECTORS, SUCH THAT NO CONSUMER IS WORSE OFF AND AT LEAST ONE IS BETTER OFF.
IN THE CASE OF ONE CONSUMER AND ONE PRODUCER IS ILLUSTRATED IN FIG- 7.

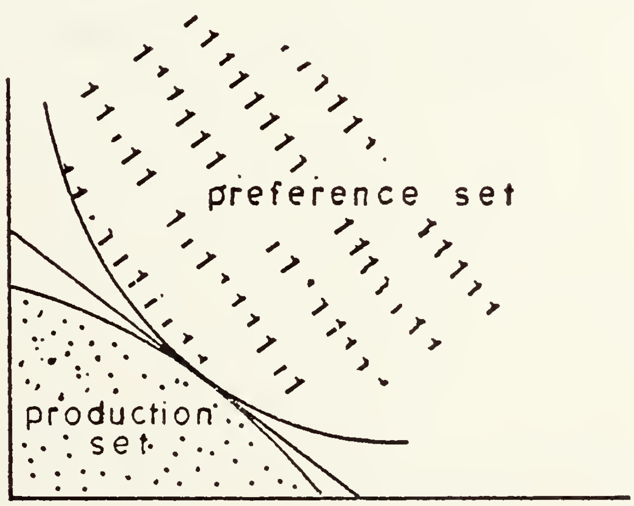


FIG-7

BY ASSUMPTION THE PREFERENCE SETS AND THE PRODUCTION POSSIBILITIES ARE CONVEX, COMPETITIVE EQUILIBRIUM IS GIVEN BY THE POINT OF TANGENCY OF THE BOUNDARY OF THE PRODUCTION FRONTIER AND THE HIGHEST ATTAINABLE INDIFFERENCE CURVE, WHERE THE VECTOR OF THE CONSUMER IS $\bar{C}^h$ AND THE I-O VECTOR OF THE FIRM IS $\bar{Y}^f$.
BY CONVEXITY ASSUMPTIONS THERE EXISTS A SEPARATING HYPERPLANE FOR WHICH THE PRODUCTION POSSIBILITIES SET LIES ON ONE SIDE AND THE PREFERENCE SET ASSOCIATED WITH THE HIGHEST ATTAINABLE WELFARE CURVE LIES ON THE OTHER SIDE OF THE HYPERPLANE. THE HYPERPLANE OR PRICE LINE FUNCTION :

$$\bar{P}^* . \bar{Z} = V$$

WHERE:

$$V = \bar{P}^* . \bar{C}^* = \bar{P}^* . \bar{Y}^*$$

IN OUR STUDY WE ASSUMED THE X VECTOR COMMODITIES REFERS TO GOODS AND SERVICES SENSITIVE TO THE OIL POLLUTION SUCH AS FISHING INDUSTRIES, RECREATION ACTIVITIES ETC.
ASSUMING THAT THE PRODUCTION POSSIBILITIES SET IS A FUNCTION OF SPILL SIZE. WE THEN ASSUME INCREASES IN POLLUTION SIZE WOULD DECREASE THE PRODUCTION OF COMMODITIES IN THE AREA FOULED BY OIL. THIS MAKES SENSE SINCE FOULED BEACHES MEAN DECREASES IN INPUT OF RECREATION PRODUCTION, AND FOULED WATERS RESULT IN REDUCED COMMERCIAL FISHING REVENUES.
IF GOODS AND SERVICES AFFECTED BY THE OIL SLICK HAVE NO MARKET VALUES OR PRICES, WE MAY USE A SHADOW PRICING SCHEME TO DETERMINE THE VALUES.

THE SHADOW PRICE OF A GIVEN (CONSTRAINED) COMMODITY IS DEFINED AS MARGINAL VALUATION OF THE COMMODITY BY RELAXING THE CONSTRAINT MEASURED IN TERMS OF THE OBJECTIVE FUNCTION .

THE SOCIAL COST C(S) OF THE OIL POLLUTION COULD THUS BE DESCRIBED AS THE DIFFERENCE IN VALUE BETWEEN THE PRODUCTION LEVEL IN THE ABSENCE OF SPILLS AND THE PRODUCTION LEVEL RESULTING FROM A SPILL.

$$C(S) = \bar{P}^*(S=0) . (\bar{X}^*(S=0) - \bar{X}^*(S=1))$$

VI. COST MODEL DEVELOPMENT.

ANY SPILLAGE OF OIL INTO THE WATERS REPRESENTS A LOSS OF PRODUCTS TO THE ECONOMY. THIS LOSS IS EQUAL TO THE MARKET VALUE OF THE PRODUCTS LOST.
IN ADDITION TO THE LOST PRODUCT, THERE WILL ALWAYS BE DAMAGE DONE TO THE AQUATIC ENVIRONMENT AND POSSIBLY TO THE SURROUNDING LAND AREAS OR BEACHES.
MANY FRACTIONS OF OIL ARE SOLUBLE OR EMULSIFIED IN THE WATER AND SINK. SUCH DISSOLVED SUBSTANCES CANNOT BE EASILY TAKEN OUT BY SIMPLE REMOVAL OF THE VISIBLE PRODUCT AND DAMAGES INFLICTED MAY NOT BE REVERSIBLE.
THE ENVIRONMENTAL DAMAGE FACTOR IS COMPLICATED BY THE EXISTENCE OF SHORT AND LONGER TIME EFFECTS.
THE LOCATION OF THE SPILL IS CRITICAL TO THE COST THAT IS INCURRED.

A. GENERAL COST MODEL.

AS WAS PREVIOUSLY MENTIONED, THE COST OF A PARTICULAR OIL SPILL C(S) :

$$C(S) = A(S) + B(S)$$

WHERE:

$A(S)$ = DIRECT COST OF OIL SPILL.

$B(S)$ = INDIRECT COST OF OIL SPILL.

B. D I R E C T C O S T .

DIRECT COST (S) IS EQUAL TO THE MARKET VALUE OF THE PRODUCT LOSS

$$A(S) = C \cdot V$$

WHERE:

V = VOLUME OF OIL SPILLED

C = MARKET PRICE PER UNIT VOLUME

S = SPILL INDICATOR.

C. I N D I R E C T C O S T.

INDIRECT COST $B(S)$, IS THE VALUATION OF COMMODITY LOSS RESULTING FROM THE OIL SPILL.

$$B(S) = \bar{C} \cdot \Delta \bar{X} = \sum_{j=1}^{N} C_j \cdot \Delta X_j \ .$$

TO SIMPLIFY THE COST MODEL TO A RESOLVABLE LEVEL, CONSIDER ONLY COMMODITIES THAT MIGHT HAVE SIGNIFICANT EFFECT IN THE CALCULATION OF COST.
ASSUME THE SIGNIFICANT INDIRECT COST WAS THE SUMMATION OF LOSS IN WILD BIRD POPULATION, LOSS IN FISH POPULATION, LOSS IN PROPERTY VALUES, LOSS TO THE BUSINESS ACTIVITIES IN COMMERCIAL FISHING AND RELATED INDUSTRIES AND LOSS TO THE RECREATION ACTIVITIES (SPORT-FISHING, BOATING, TOURISM ETC)

THUS IN OUR MODEL COST, N EQUAL TO FIVE, WE DENOTE :

C_1 = RELATIVE PRICE (WEIGHTING FACTOR) OF A BIRD.

ΔX_1 = NUMBER OF BIRDS KILLED.

THE RELATIVE PRICE REFLECTS THE SHADOW PRICE WHICH IS PRESUMABLY DETERMINED UNDER SOME APPROPRIATE CONSTRAINED MAXIMIZATION PROBLEM.

C_2 = RELATIVE PRICE OF A FISH

ΔX_2 = NUMBER OF FISH KILLED

AS IN C-1 ,USE SHADOW PRICE TO DETERMINE THE RELATIVE PRICE C-2 OF A FISH. IN THIS CASE THE FISH ARE NOT VALUED AT THEIR MARKET PRICE TO AVOID DOUBLE COUNTING, SINCE THE EFFECT ON THE MARKET IS COMPUTED BELOW AS THE REDUCTION OF OUTPUT IN THE COMMERCIAL FISHING ACTIVITY. THE SHADOW PRICE REPRESENTS THE LONG TERM EFFECTS AND ALSO REPRESENTING THE REAL OBVIOUS LOSS IN THE NATURAL RESOURCE BASE.

C_3 = DROP IN MARKET PRICE OF PROPERTY VALUE PER UNIT AREA RELATIVE TO THE BASE PRICE.

ΔX_3 = AREA OF VALUABLE BEACHES/COAST FOULED BY OIL.

C-4 IS A FUNCTION OF LOCATION. IN OUR STUDY WE DIVIDE SAN FRANCISCO BAY AREA INTO FIVE DIFFERENT LOCATIONS. THIS COULD BE REFINED INTO ON THE SPOT LOCATION AS PREDICTED BY THE SIMULATION TECHNIQUE. IN REALITY WE SHOULD ALWAYS USE MUCH FINER GRID SYSTEM TO OBTAIN A MORE ACCURATE COST PICTURE.

C_4 = MARKET PRICE PER UNIT PRODUCT OF COMMERCIAL FISHING ACTIVITIES (AND RELATED INDUSTRIES) RELATIVE TO THE BASE PRICE.

ΔX_4 = REDUCTION ON PRODUCTION CAPACITY OF COMMERCIAL FISHING ACTIVITIES (AND RELATED

INDUSTRIES).

C_5 = MARKET PRICE PER UNIT PRODUCT OF RECREATION ACTIVITY RELATIVE TO THE BASE PRICE.

ΔX_5 = REDUCTION IN PRODUCTION CAPACITY OF RECREATION ACTIVITY.

D. DETERMINISTIC MODEL TO ESTIMATE BIRD OR FISH DEATH.

TO ESTIMATE THE BIRD OR FISH KILLED, WE USE DIFFERENTIAL EQUATION AS FOLLOWS:

$$\frac{dX}{dt} = -k.Y$$

WHERE :

k = DEATH RATE OF BIRDS OR FISH AS A FUNCTION OF LOCATION, SIZE AND TYPE OF OIL SPILL.

TYPE OF OIL RELATES WITH ITS TOXICITY.

Y = AREA SPILLED AS A FUNCTION OF TIME.

SOLVE THE EQUATION BY USING EULER APPROXIMATION TECHNIQUE:

NUMBER OF BIRDS OR FISH KILLED = ΔX

$$\Delta X \Big|_{t=T} = k.\Delta t. \sum_{J=1}^{M} Y_j$$

E. DETERMINISTIC MODEL TO ESTIMATE PROPERTY DAMAGE.

IF THE OIL SLICK LANDED ON THE SHORE, THUS THE SOCIAL COST OF DAMAGE WOULD BE CONSIDERED TO BE EQUAL TO THE LOSS OF VALUE IN MARKET PRICE OF THE PROPERTY FOULED BY OIL.

$$\Delta X_3 \cong \pi R_f^2$$

$$C_3.\Delta X_3 = C_3.\pi.R_f^2$$

πR_f^2 REPRESENT THE AREA FOULED BY OIL. R_f MAY BE OBTAINED FROM THE SIMULATION.

F. MODEL TO ESTIMATE THE SOCIAL COST OF BUSINESS ACTIVITY.

THE STANDARD PRODUCTION FUNCTION MODEL IS A SUFFICIENTLY WELL KNOWN TOOL OF ECONOMIC ANALYSIS.
TO MAKE THE MODEL TRACTABLE, WE SIMPLIFY BY ASSUMING THAT ONLY A SINGLE FIRM POSSESSES ALL BUSINESS ACTIVITIES IN THE BAY AREA, AND THE EXISTENCE OF SOCIAL PREFERENCE OVER RECREATION AND COMMERCIAL FISHING ACTIVITIES.
ASSUME THE PRODUCTION POSSIBILITIES SET OF THE FIRM IS KNOWN AS FOLLOWS :

$$\emptyset \equiv \frac{X^2}{a^2} + \frac{Y^2}{b^2} - 1 = 0$$

WHERE :

X = PRODUCT OF RECREATION ACTIVITY

Y = PRODUCT OF COMMERCIAL FISHING (AND RELATED INDUSTRIES)

$a \geqslant 0 \quad , b \geqslant 0$

a , b IS A FUNCTION OF SPILL SIZE AND LOCATION.

$$a = a_0 \left(\delta_1 e^{-\delta_2 V^2} + \delta_3 \right)$$

$$b = b_0 \left(\varepsilon_1 e^{-\varepsilon_2 V^2} + \varepsilon_3 \right)$$

δ_1 = THE PROPORTION OF PRODUCTION RELATED WITH THE BAY ACTIVITIES (SWIMMING, SPORT FISHING ETC)

δ_2 = DEGRADATION CONSTANT

δ_3 = THE PROPORTION OF PRODUCTION NOT RELATED TO THE BAY ACTIVITIES FOR EXAMPLE PEOPLE IN TRANSIT ETC

ε_1 = THE PROPORTION OF PRODUCTION WITH LOCAL INPUT RESOURCES.

ε_2 = DEGRADATION CONSTANT

ε_3 = THE PROPORTION OF PRODUCTION WITH INTERLOCAL INPUT RESOURCES.

V = VOLUME, SPILL SIZE.

a_0 , b_0 = MAXIMUM PRODUCTION LEVEL FOR EACH ACTIVITY GIVEN ALL AVAILABLE RESOURCES.

a_0 , b_0 , δ , ε IS A FUNCTION OF LOCATION.

THE SOCIAL PREFERENCE FUNCTION IS GIVEN AS :

$$W(s) = c \cdot X^{\alpha} \cdot Y^{\beta}$$

WHERE :

C = CONSTANT, GIVEN AS A FUNCTION OF LOCATION.

α, β : KNOWN AS GIVEN AND $\alpha + \beta < 1$, $\alpha \geq 0$, $\beta \geq 0$.

BY ASSUMING THAT THE FIRM TREATS PRICES AS GIVEN AND SEEKS TO MAXIMIZE ITS PROFIT,
MAXIMIZE ITS PROFIT,

MAX $= P_x \cdot X + P_y \cdot Y$

SUBJECT TO $\dfrac{X^2}{a^2} + \dfrac{Y^2}{b^2} - 1 = 0$

BY USING LAGRANGE MULTIPLIER TECHNIQUE, THEN

PROFIT IS MAXIMIZED IF :

$$X_0 = \frac{P_x \cdot a^2}{\sqrt{a^2 P_x^2 + b^2 P_y^2}}$$

$$Y_0 = \frac{P_y \cdot b^2}{\sqrt{a^2 P_x^2 + b^2 P_y^2}}$$

ON THE CONSUMER SIDE, GIVEN BUDGET CONSTRAINT, MAXIMIZE HIS PREFERENCES

MAX $W(S) = C \cdot X \cdot Y$

SUBJECT TO $Z = P_x \cdot X + P_y \cdot Y$

USING LAGRANGE MULTIPLIER TECHNIQUE :

PREFERENCES ARE MAXIMIZED IF :

$$X_o' = \frac{\alpha Z}{P_x(\alpha+\beta)}$$

$$Y_o' = \frac{\beta Z}{P_y(\alpha+\beta)}$$

EQUILIBRIUM CONDITION IF: $Z = \pi = \pi^*$

THE CONDITION APPLIES IF :

$$X_e = \left(\frac{\alpha a^2}{\alpha+\beta}\right)^{1/2}$$

$$Y_e = \left(\frac{\beta b^2}{\alpha+\beta}\right)^{1/2}$$

THE SUPPLY AND DEMAND CURVES OF 'X' PRODUCT ARE :

$$X_S = \frac{a^2 P_x^*}{\pi^*}$$

$$X_D = \frac{\alpha \pi^*}{P_x^*(\alpha+\beta)}$$

THE SUPPLY AND DEMAND CURVES OF 'Y' ARE :

$$Y_S = \frac{b^2 P_y^*}{\Pi^*}$$

$$Y_D = \frac{\beta . \Pi^*}{P_y^* (\alpha + \beta)}$$

WHERE : $\Pi^* = (a^2 P_x^{*2} + b^2 P_y^{*2})^{1/2}$

THE PRICE FUNCTION IS :

$$P_y^* = P_x^* \frac{Y_e . a}{b(b^2 - Y_e^2)^{1/2}}$$

G. SENSITIVITY ANALYSIS.

AS AN EXAMPLE WE ANALYSE THE CHANGES IN SUPPLY CURVES AS WE CHANGE THE PRODUCTION POSSIBILITY PARAMETER :

CHANGES IN SUPPLY CURVES :

$$\frac{\partial Y_S}{\partial a} = \frac{a . b^4 (P_x / P_y)^2}{(a^2 (P_x/P_y)^2 + b^2)^{3/2}} \leqslant 0$$

$$\frac{\partial X_S}{\partial a} = \frac{a^2 + 2b^2 (P_y/P_x)^2}{a (a^2 + b^2 (P_y/P_x)^2)^{3/2}} \geqslant 0$$

CONCLUSION :

1. IF 'A' DECREASES, THE SUPPLY CURVE OF 'X' WILL SHIFT TO THE LEFT, IF 'A' INCREASES CONVERSE HOLDS

2. IF 'A' DECREASES THE SUPPLY CURVE OF 'Y' WILL SHIFT TO THE RIGHT, IF 'A' INCREASES CONVERSE HOLDS.

CHANGES IN DEMAND CURVES :

$$\frac{\partial Y_D}{\partial a} = \frac{2\, a\, \beta\, P_x^2}{P_y\,(\alpha + \beta)} \left(a^2 P_x^2 + b^2 P_y^2 \right)^{-1/2} \geqslant 0$$

$$\frac{\partial X_D}{\partial a} = \frac{2 . a . \alpha . P_x}{(\alpha + \beta)} \left(a^2 P_x^2 + b^2 P_y^2 \right)^{-1/2} \geqslant 0$$

CONCLUSION :

1. IF 'A' DECREASES, BOTH DEMAND FOR 'X' AND 'Y' WILL SHIFT TO THE LEFT.

2. IF 'A' INCREASES, CONVERSE HOLDS.

CHANGE IN THE EQUILIBRIUM POINT :

$$\frac{\partial Y_e}{\partial a} = 0$$

$$\frac{\partial X_e}{\partial a} = \frac{2\, a\, \alpha}{\alpha + \beta} \left(\frac{a^2 \alpha}{\alpha + \beta} \right)^{-1/2} \geqslant 0$$

CONCLUSION :

1. NO CHANGE IN 'Y' PRODUCTION LEVEL.

2. IF 'A' DECREASES, THE PRODUCTION LEVEL OF 'X' WILL DECREASE, IF 'A' INCREASES , CONVERSE HOLDS.

THE SOCIAL COST OF A SPILL IS EQUAL TO THE MARKET VALUE OF THE PRODUCT LOSSES.

$$\text{SOCIAL COST} = P_x \cdot (X_e - X_e') + P_y \cdot (Y_e - Y_e')$$

WHERE :

P_x AND P_y REPRESENT THE PRICE PER UNIT PRODUCT OF X AND Y,

X_e AND Y_e REPRESENT THE OPTIMUM PRODUCTION LEVEL OF X AND Y BEFORE THE SPILL OCCURS.

X_e' AND Y_e' REPRESENT THE OPTIMUM PRODUCTION LEVEL OF X AND Y AFTER THE SPILL OCCURS.

SEE FIGURE 8A,B ; FIGURE 9A, ; FIGURE 10A,B FOR GRAPHICAL ILLUSTRATION.

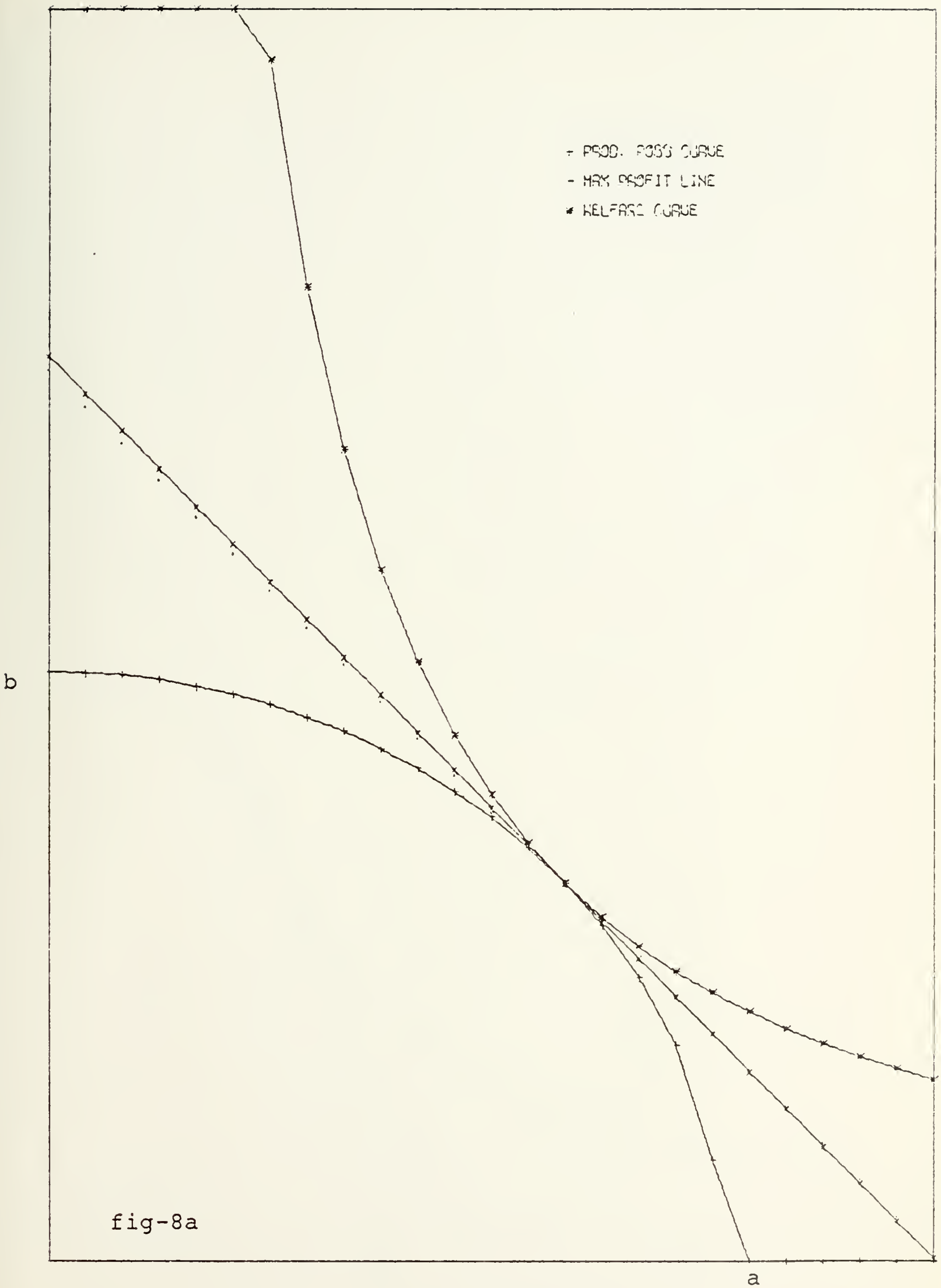
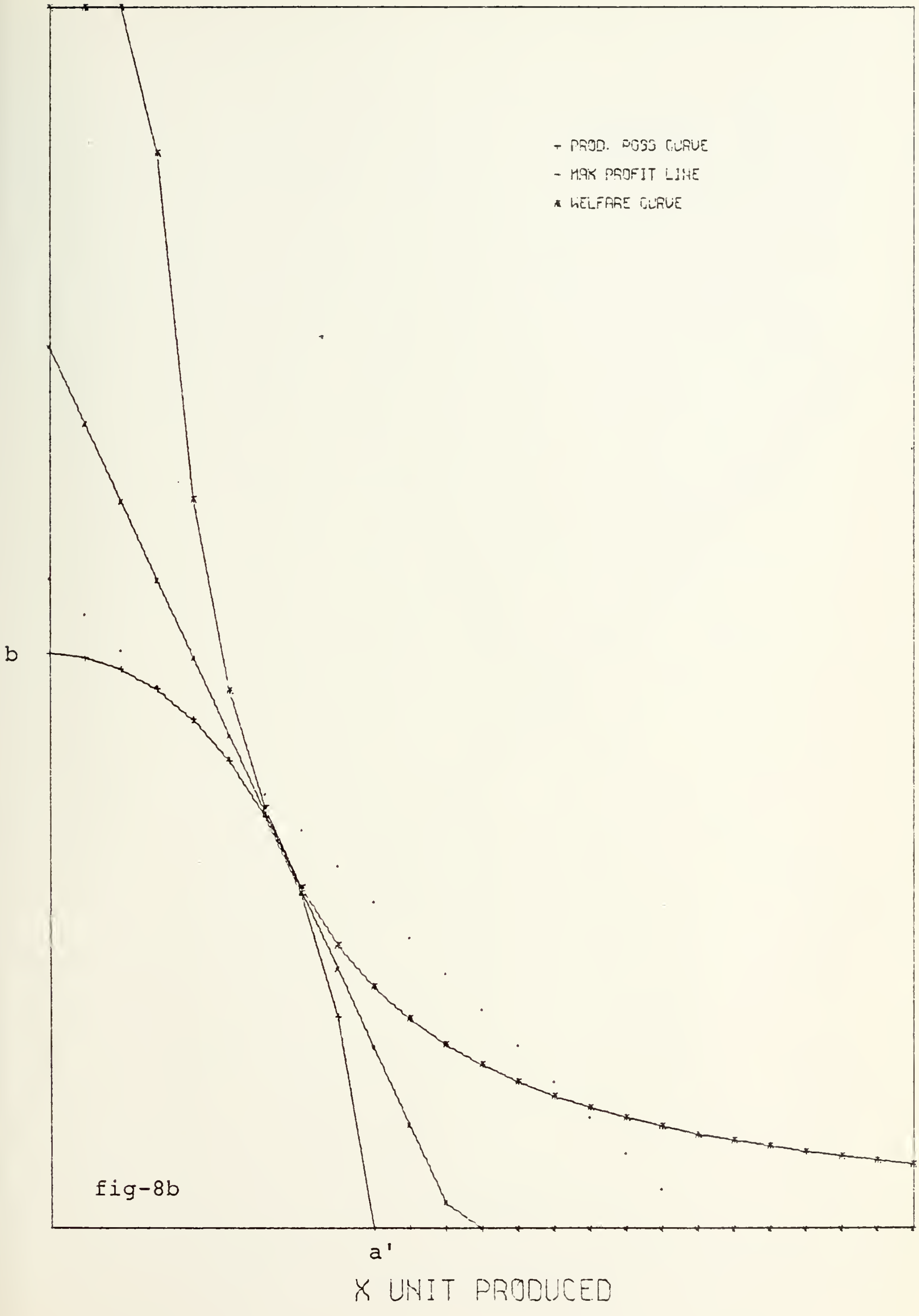


fig-8a

X UNIT PRODUCED



+ PROD. POSS CURVE
- MAX PROFIT LINE
* WELFARE CURVE
b
a'
fig-8b
X UNIT PRODUCED

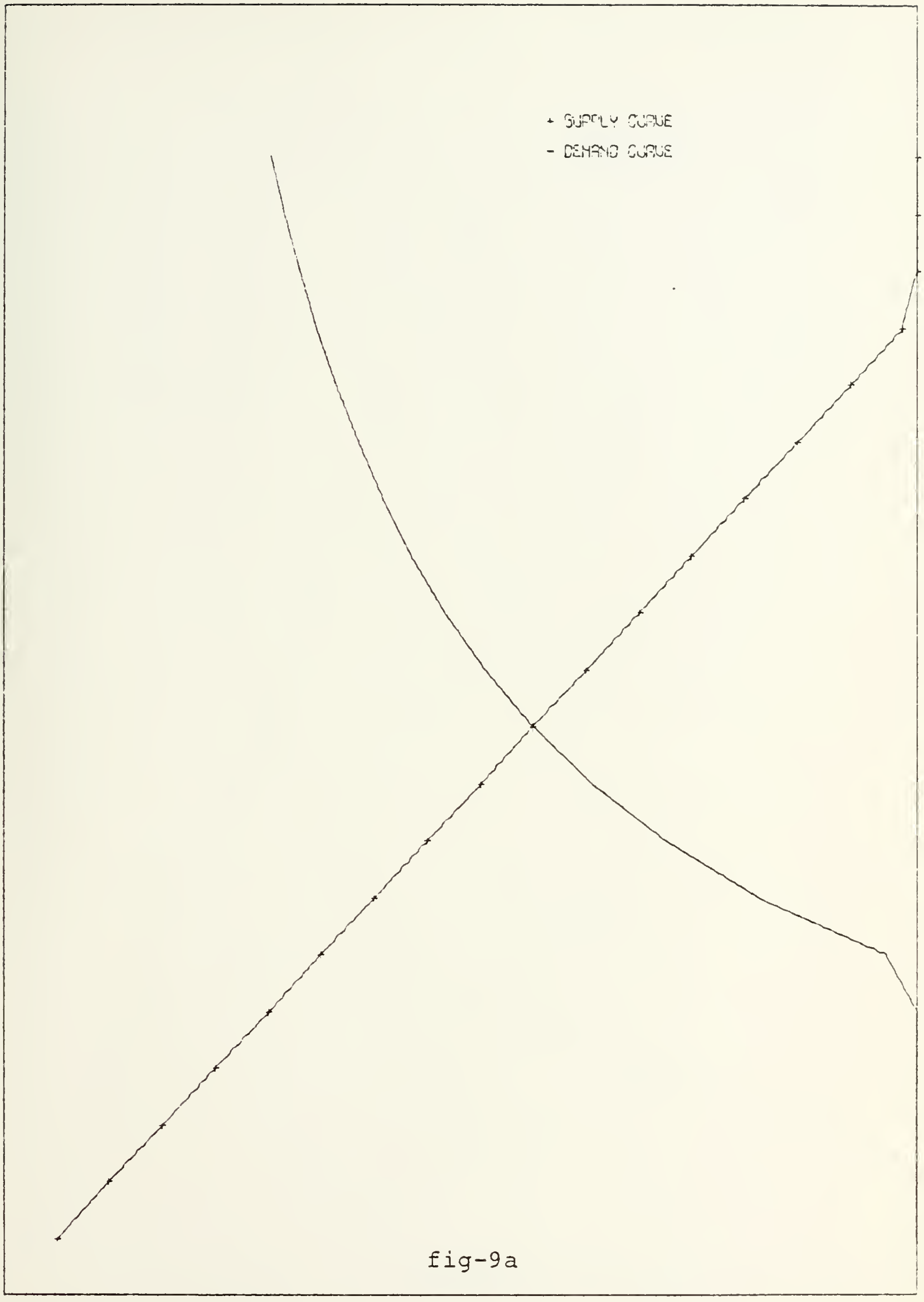


fig-9a

X UNIT PRODUCED

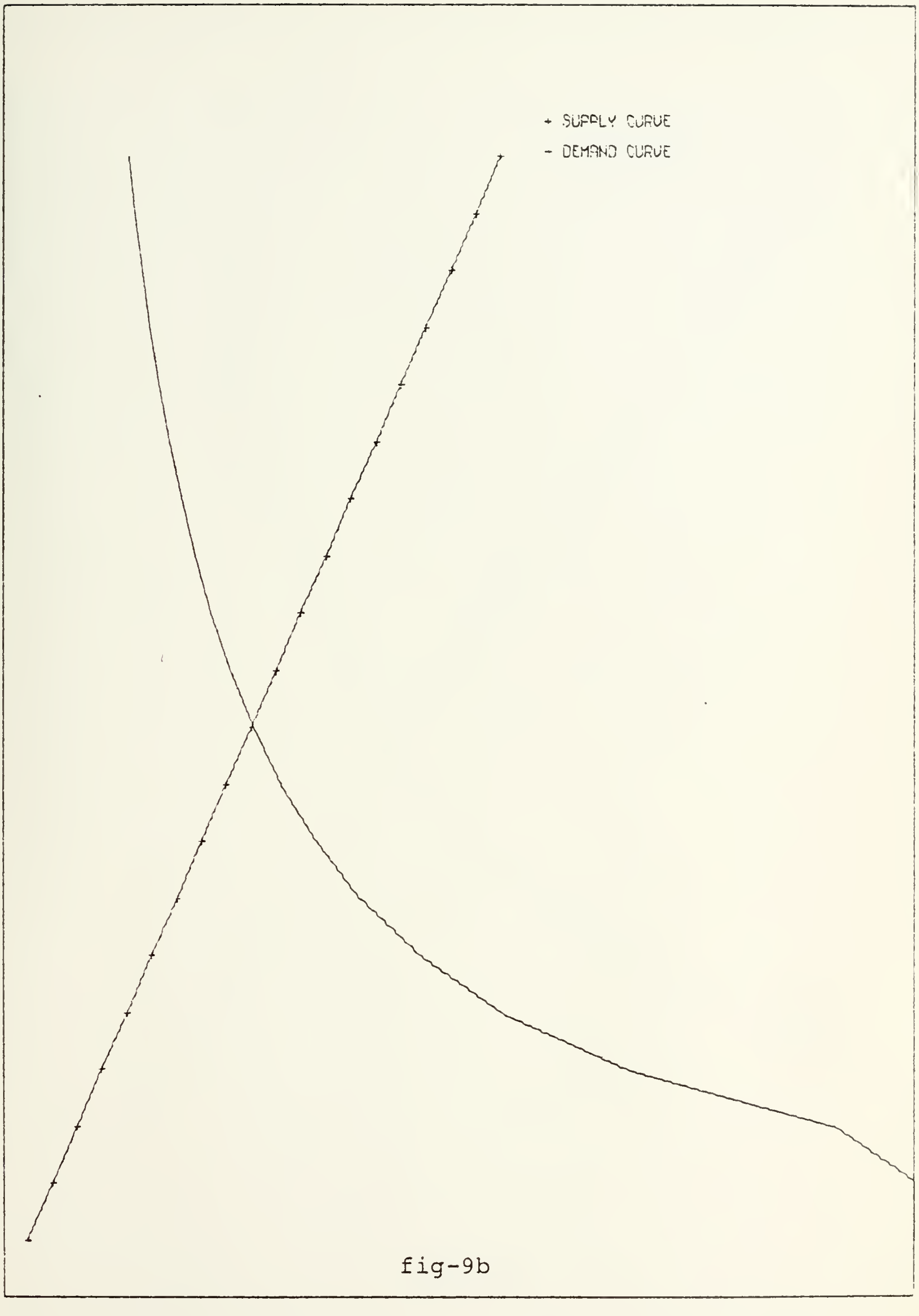


fig-9b

X UNIT PRODUCED

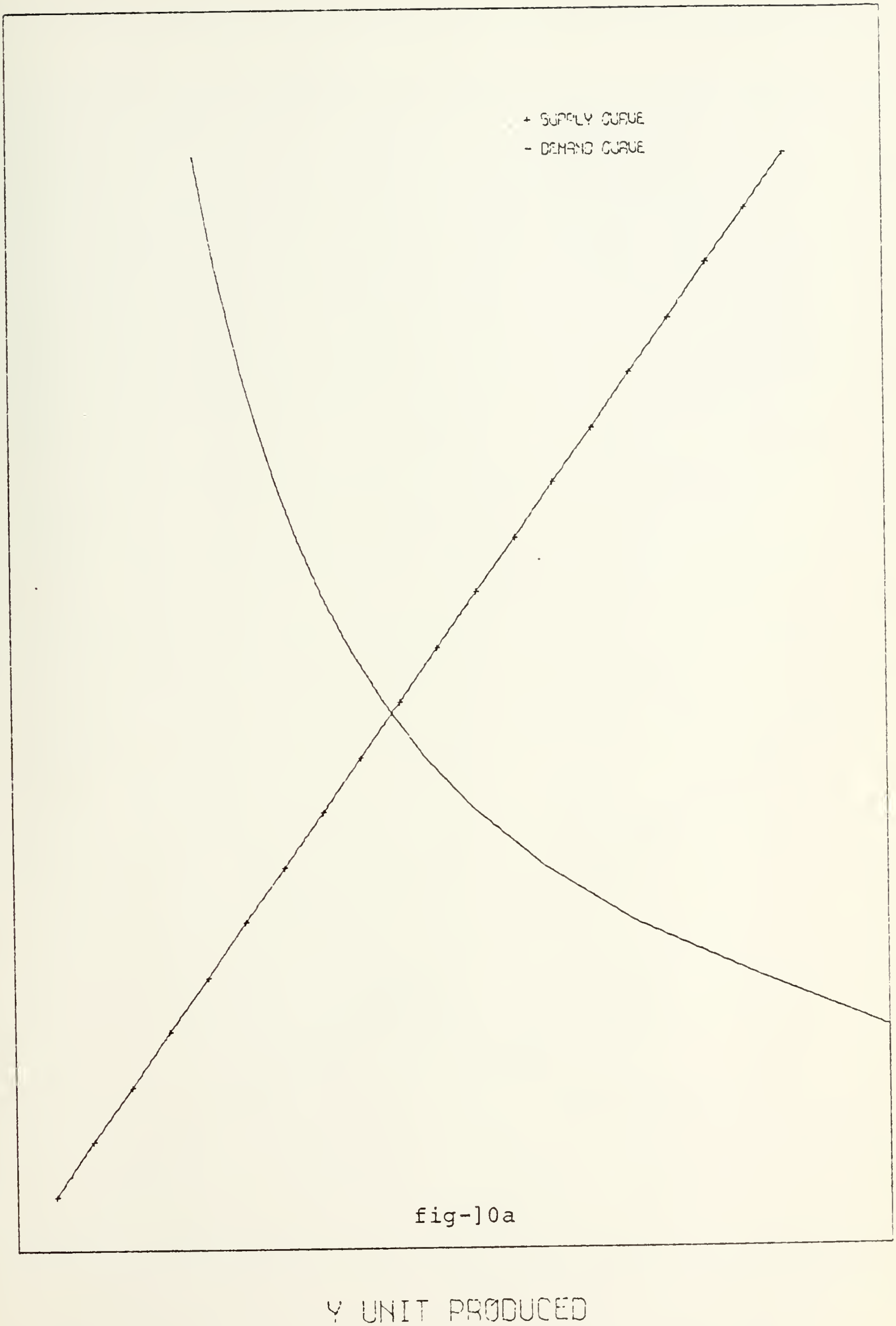


fig-10a

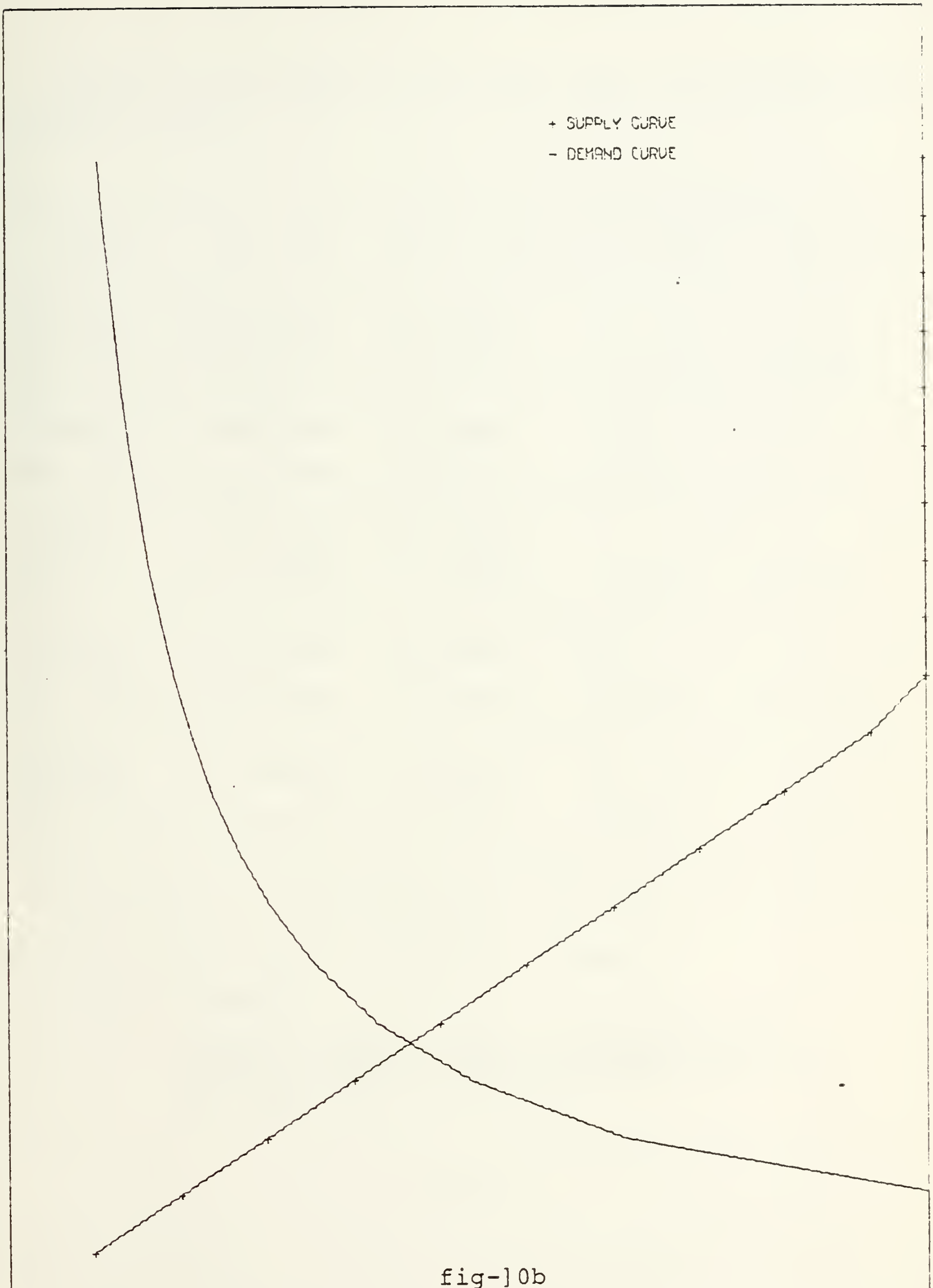


fig-]0b

Y UNIT PRODUCED

VII. DATA ANALYSIS

ASSUME THE PARAMETERS OF THE COST MODEL IN THIS STUDY ARE SHOWN IN TABLE-2

REGION	PROD. PARM	BEACH VALUE	BIRD PARM	FISH PARM
SOUTHERN BAY / EAST	a_0 =40,000 b_0 =10,000	H=4,000 N L=2,500 N	C_1 = 2 N k_1 =0.01	C_2 = 2 N k_2 =0.12
SOUTHERN BAY / WEST	a_0 =60,000 b_0 =40,000	H=6,000 N L=3,500 N	C_1 = 3 N k_1 =0.01	C_2 = 3 N k_2 =0.10
CENTRAL BAY	a_0 =100,000 b_0 = 50,000	H=7,000 N L=3,500 N	C_1 = 5 N k_1 =0.05	C_2 = 2 N k_2 =0.05
NORTHERN BAY / EAST	a_0 =20,000 b_0 =30,000	H=4,000 N L=1,500 N	C_1 = 3 N k_1 =0.10	C_2 = 4 N k_2 =0.15
NORTHERN BAY / WEST	a_0 =100,000 b_0 =100,000	H=8,000 N L=5,000 N	C_1 = 10 N k_1 =0.10	C_2 = 10 N k_2 =0.15

* N=NUMERAIRE ; BASE PRICE, ONE LITER OIL = ONE NUMERAIRE
* BEACH VALUE : N PER HECTARE.
* BIRD (FISH) VALUE : N PER UNIT KILLED.
* PARM = PARAMETER
* H & L : H STANDS FOR THE VALUE OF BEACH OR OTHER PROPERTY PRIOR TO THE OIL SPILLAGE AND L AFTER THE SPILL, THUS THE MARKET VALUE OF THE LOSS (C_3) IS GIVEN BY : $C_3 = H - L$.

TABLE-2

THE RECREATION & COMMERCIAL FISHING COST MODEL PARAMETERS:

$\delta_1 = 0.9$ $\qquad \varepsilon_1 = 0.75$

$\delta_2 = 10^{-12}$ $\qquad \varepsilon_2 = 25\times10^{-12}$

$\delta_3 = 0.1$ $\qquad \varepsilon_3 = 0.25$

$\alpha = 0.45$ $\qquad \beta = 0.33$

$P_x = 150.$ N $\qquad P_Y$ = VARIES AS A FUNCTION OF P_x

COO = COORDINATE, COMPUTED IN METERS FROM THE ORIGIN
LATITUDE : 37° 25' N
LONGITUDE : 122° 35' W

USING THESE PARAMETERS WE OBTAINED FROM THE COMPUTER SIMULATION VALUES OF LOSSES IN RECREATION AND COMMERCIAL FISHING (AND RELATED INDUSTRIES) ACTIVITIES TABULATED IN TABLE-3.

LOSS IN RECREATION ACT. AND COMMERCIAL FISHING ACT.

	VOLUME (LITERS)		
LOCATION	10,000	100,000	1,000,000
SOUTHERN BAY/EAST	6,671.	595,255.	5,099,228.
SOUTHERN BAY/WEST	10,005.	892,882.	7,648,843.
CENTRAL BAY	16,671.	1,488,135.	12,748,060.
NORTHERN BAY/WEST	16,673.	1,488,138.	12,748,066.
NORTHERN BAY/EAST	3,335.	297,626.	2,549,613.

TABLE - 3

TO OBTAIN THE SOCIAL COST OF ANY POLLUTION ACCIDENTS IN SAN FRANCISCO BAY AREA, GIVEN THE LOCATION OF THE ACCIDENT THE COMPUTER SIMULATION AS SHOWN ON APPENDIX A WILL GIVE THE PREDICTION OF THE SPREAD AND MOVEMENT OF OIL AFFECTED BY THE WIND (RANDOMLY CHOSEN), THE SURFACE MOVEMENT OF WATER BY ESTUARINE NON TIDAL DRIFT AND THE DEPLETION OF OIL DUE TO EVAPORATION.
SIX EXAMPLE OF COMPUTING THE SOCIAL COST WAS OBTAINED AS FOLLOWS :

SAMPLES OF COMPUTING THE SOCIAL COST USING THE COMPUTER SIMULATION TECHNIQUE:

1. COC : (20200;50700) — T_{12} = 0.4 HRS
   VOL : 100,000. LTRS — T_{23} = 1.9 HRS
   R_f : 398 METERS — T_f = 5.8 HRS

LOCATION	AREA FLD	BEACH FLD	DEAD BIRD	DEAD FISH
CENTRAL BAY	4234.1	49.8	212	635

SOCIAL COSTS = 1,764,765. N

2. COO : (20200;50700) — T_{12} = 0.9 HRS
   VOL : 1,000,000. LTRS — T_{23} = 8.9 HRS
   R_f : 944 METERS — T_f = 13.3 HRS

LOCATION	AREA FLD	BEACH FLD	DEAD BIRD	DEAD FISH
CENTRAL BAY	6940.	280.	347	1041

SOCIAL COSTS = 14,731,877. N

3. COO : (29000;64500) — T_{12} = 0.2 HRS
   VOL : 10,000 LTRS — T_{23} = 0.4 HRS
   R_f : 168 METERS — T_f = 1,8 HRS

LOCATION	AREA FLD	BEACH FLD	DEAD BIRD	DEAD FISH
NORTHERN BAY WEST	29.4	NONE	3	5

SOCIAL COSTS = 26,753. N

. COO : (29000;64500)

VOL : 1,000,000 LTRS

R_f : 944 METERS

T_{12} = 0.9 HRS

T_{23} = 8.9 HRS

T_f = 18.3 HRS

LOCATION	AREA FLD	BEACH FLD	DEAD BIRD	DEAD FISH
NORTHERN BAY WEST	2089.6	78.3	209	313

SOCIAL COSTS = 13,988,186. N

5. COO : (36000;21000)

VOL : 1,000,000 LTRS

R_f : 944 METERS

T_{12} = 0.9 HRS

T_{23} = 8.9 HRS

T_f = 18.3 HRS

LOCATION	AREA FLD	BEACH FLD	DEAD BIRD	DEAD FISH
SOUTHERN BAY WEST	2,432.	NONE	24	243
CENTRAL BAY	11,705.5	280.	1,171	11,706

SOCIAL COSTS = 22,406,971. N

6. COO : (37500;18500)

VOL : 100,000 LTRS

R_f : 398 METERS

T_{12} = 0.4 HRS

T_{23} = 1.9 HRS

T_f = 5.8 HRS

LOCATION	AREA FLD	BEACH FLD	DEAD BIRD	DEAD FISH
SOUTHERN BAY EAST	1,640.	NONE	16	197

SOUTHERN BAY WEST	3,168.	50.	32	380

SOCIAL COSTS = 1,714,799.

THE AGGREGATE LOSSES SHOW THE SIGNIFICANT DIFFERENCE BETWEEN SMALL AND LARGE SPILLS.
THE MOST SIGNIFICANT ECONOMIC LOSSES ARE SUFFERED BY THE BUSINESS ACTIVITIES IN THIS ILLUSTRATION.
NO ATTEMPT HAS BEEN MADE IN THIS STUDY TO FORMULATE THE LONG TERM SOCIAL COST OF OIL SPILLS.
THE MAGNITUDE OF COMPUTED VALUES IN THIS ILLUSTRATION NATURRALLY DEPEND UPON THAT OF THE PARAMETERS, WHOSE VALUES ARE ARBITRARILY CHOSEN, BUT ILLUSTRATIVE OF POSSIBLE REAL WORLD SITUATIONS.

VIII. C O N C L U S I O N

THE PURPOSE OF THIS THESIS IS TO DETERMINE THE SOCIAL COSTS OF OIL SPILLS.
THE REALIZATION THAT SUCH COSTS DEPEND ON THE ORIGINAL LOCATION AND SIZE OF A SPILL AND THE EVENTUAL AREA AFFECTED NECESSITATES DEVELOPMENT OF A MODEL WHICH PREDICTS HOW A GIVEN OIL SPILL WILL SPREAD UNDER PLAUSIBLE CIRCUMSTANCES.
FOR THIS WE HAVE SYNTHESIZED THE WORKS OF FAY (REF-6), SMITH (REF-4), SIVADIER AND MIKOLAJ (REF-1) , CONOMOS (REF-5) BY INCORPORATING WIND (RANDOMIZED DIRECTION AND VELOCITY), ESTUARINE NON TIDAL DRIFT AND EVAPORATION FACTOR.
IN ORDER TO DETERMINE SOCIAL COSTS OF AN OIL SPILL WE ALSO NEED TO IDENTIFY THE COST COEFFICIENTS OF FACTORS DAMAGED SUCH AS WILDLIFE, RECREATIONAL AND COMMERCIAL ACTIVITIES, ETC. EXACT DETERMINATION OF THESE COEFFICIENTS IS BEYOND THE SCOPE OF THIS PAPER. THUS IN THE QUANTITATIVE ANALYSIS GIVEN HERE FOR ILLUSTRATION, THEY ARE GIVEN PLAUSIBLE, BUT ARTIFICIAL VALUES.

A P P E N D I X   A

COMPUTER SIMULATION PROGRAM OF THE SPREAD AND MOVEMENT OF OIL SLICK IN SAN FRANCISCO BAY

```
//HAN1874 JOB (2696,1446,RL44),'MUDJIARDJO SMC 1874'
// EXEC FORTCLGP,REGION.GO=180K
//FORT.SYSIN DD *
C THESIS THESIS THESIS THESIS THESIS THESIS THESIS THESIS TH
C
C   THE SPREAD AND MOVEMENT OF OIL SLICKS ON THE WATERS.
C
C     OSL = OIL SLICK LEEWAY
C WIND = WIND SPEED MEASURED AT 10 METERS ELEVATION IN KNOTS
C
C AN ESTIMATE OF WIND DRIVEN SURFACE CURRENT MAY BE OBTAINED
C FROM THE FOLLOWING EQUATION PROPOSED BY THORADE (1914) :
C      SCW = SURFACE CURRENT DRIVEN BY THE WIND
C      PHI = GEOGRAPHICAL LATITUDE
C      SCW = 0.0361 * SQRT(WIND)/SQRT((SIN(PHI))
C      IF( WIND .GT. 11.64 ) SCW=0.0126*WIND/SQRT((SIN(PHI))
C
C
      DIMENSION TIMES(80), RADIUS(80)
      DIMENSION X( 80), Y( 80)
      DIMENSION CCAA(900), DDAA(900)
      DIMENSION OSLV(80), SCWV(80), WINDV(80)
      DIMENSION DELT( 80),HTT( 80)
      DIMENSION CC( 80, 80) , DD( 80, 80)
      DIMENSION CCA( 6400), DDA( 6400)
      EQUIVALENCE(CCA,CC),(DDA,DD)
      DIMENSION XMV(80), YMV(80)
      DIMENSION XP(200), YP(200),XO(200),YO(200)
      DIMENSION  DZ(100), HZ(100), VXL(80)
      DIMENSION XQ(200),YQ(200),XR(200),YR(200)
      DIMENSION XS(200),YS(200),XT(200),YT(200)
      DIMENSION XU(200),YU(200),XV(200),YV(200)
      DIMENSION AX(800),AY(800)
   96 FORMAT( 6F5.1 )
   97 FORMAT( 2F10.1 )
   98 FORMAT( F10.3 )
   99 FORMAT( 5I3 )
  100 FORMAT(/,10X,'M=',I3,3X,'N=',I3,3X,'KK=',I3,3X,'NK=',
     1I3,3X,'KX=',I3,3X,'XMV(1)=',F8.1,3X,'YMV(1)=',F8.1 )
  101 FORMAT(/,10X,'VOLUME OF OIL SPILLED IN LITERS=',F12.1)
  102 FORMAT(10X,'RADIUS OF SLICK, M',3X,'AT TIME, HRS',
     23X,'THICK OF OIL,CM',3X,'THICK OF OIL PARTICLES,CM',
     33X,'VOL IN LTRS',3X,'NO:')
  103 FORMAT(15X,F8.2,11X,F6.1,10X,F7.3,15X,F7.3 ,12X,F10.1,
     45X,I3 )
  104 FORMAT(//,18F8.2 )
  105 FORMAT( 18F8.2 )
  106 FORMAT(/,10X,'MAXIMUM RADIUS OF OIL SLICK IN METERS=',
     5F8.2 )
  107 FORMAT(///)
  108 FORMAT( '*******************************************
     6********************************************************')
  109 FORMAT(/,10X,' CRITICAL THICKNESS IN CM:',F7.3 )
  110 FORMAT(/,10X,'THICKNESS OF MOL. DIFFUSION, CM=',F7.3)
  111 FORMAT(/,10X,' TIME REQUIRED AS INFINITY, HRS:',F6.1 )
  112 FORMAT( '1' )
  113 FORMAT(10X,'GAMA1=',F5.1,3X,'GAMA2=',F5.1,3X,'GAMA3=',
     7F5.1,3X,'GAMA4=',F5.1,3X,'GAMA5=',F5.1,3X,'GAMA6=',
     8F5.1 )
  114 FORMAT(/,10X,'T12 = ',F6.1,3X,' T23 = ',F6.1 )
```

```
  201 FORMAT(10X,F9.3,3X,F9.3,3X,F9.3,3X,F9.2,4X,F9.2,6X,I3)
  202 FORMAT(13X,'WIND',8X,'OSL',9X,'SCW',10X,'XMV',10X,
     1'YMV',8X,'NO:'   )
  203 FORMAT( / )
  300 FORMAT ( 16F5.1 )
  301 FORMAT( 16F8.2 )
  302 FORMAT( 16F5.2 )
  303 FORMAT(/,10X,' RADIUS OF OIL =',F8.2 ,' NZ= ',I4 )
  304 FORMAT(/,10X,'TOTAL AREA FOULED IN HECTARE=',F14.1 )
C
C                               R  E  A  D
C###################################################################
C GAMMA = ANGLE BETWEEN THE WIND VECTORS AND THE COORDINATE
C SYSTEM
      READ(5,96) GAMA1, GAMA2, GAMA3, GAMA4, GAMA5, GAMA6
C     SPILL COORDINATE MEASURED FROM ORIGIN IN METERS.
      READ(5,97) XMV(1), YMV(1)
C GIVE THE INPUT DATA OF THE QUANTITY OF OIL SPILLED IN KILO
C LITERS.
C     1 KILO LITER = 1000 LITERS.
      READ(5,98) QTT
C     M,N,KK = FIXED NUMBER OF COORDINATE POINTS OF SAN FRAN
C CISCO BAY AREA AND CURRENT VECTORS ON THE BAY AS PREDICTED
C BY ESTUARINE NONTIDAL DRIFT TO BE PLOTTED BY THE COMPUTER.
C     NK : NUMBER OF ITERATION RELATED TO TIME NEEDED TO
C     ESTIMATE THE OIL MOVEMENT.
C     KX : NUMBER OF ITERATION TO COMPUTE THE COORDINATE OF
C     THE OIL SPREAD.
C     LIMIT OF (NK*KX) = 900 POINTS.
      READ(5,99) M, N, KK, NK, KX
C     COORDINATE POINTS TO DRAW SF BAY AREA.
      READ(5,300) ( XO(I), I=1,KK )
      READ(5,300) ( YO(I), I=1,KK )
C THE COORDINATE POINTS TO DRAW THE ESTUARINE NON TIDAL
C DRIFT.
      READ(5,302) (AX(I),I=1,N )
      READ(5,302) (AY(I),I=1,N )
C THE COORDINATE POINTS TO DRAW THE ESTUARINE NON TIDAL
C DRIFT CONTINUED
      READ(5,302) (XR(I),I=1,M)
      READ(5,302) (YR(I),I=1,M)
C###################################################################
C
C
      C1 = 0.53
      C2 = 0.026
      ZU = 0.01
      RHOIL = 0.95
      RHOWAT = 1.0
      GRAV = 980.0
      D = 1.0
      SIGMA = 10.
      PHI = 38.
      IX = 1234567
C
      DELRHO= RHOWAT - RHOIL
      DELTA= DELRHO/RHOIL
      VOL = QTT*1000000.0
      VOLUME = VOL/1000.
C
C                               C O M P U T E
C>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
C COMPUTE THE CRITICAL THICKNESS OF THE OIL SLICK.
      HC = ( SIGMA/(DELRHO * GRAV))**.5
      WRITE(6,112)
      WRITE(6,108)
      WRITE(6,100) M, N, KK, NK, KX, XMV(1), YMV(1)
      WRITE(6,113) GAMA1, GAMA2, GAMA3, GAMA4, GAMA5, GAMA6
      WRITE(6,101) VOLUME
      WRITE(6,109) HC
C MAXIMUM RADIUS OF OIL SLICK AS ONE UNIT AT ZERO GROWS RATE
C ( INDEPENDENT OT TIME )
```

```
      VVV =  VOLUME/1000.
      REND = 100. * ( 10.**5*VVV**0.75/ 3.14 )**0.5
      CALL RANDU(IX,IY,YFL)
      C3 = 0.78 + YFL*0.02
C END RADIUS REDUCED DUE TO EVAPORATION
      REND = REND * C3 /2.
      TINF=(REND/2.3)**4*RHOWAT**2*ZU/SIGMA**2
      TINF = TINF**0.33333
      HINF = SQRT( TINF*D/10.**5)
      TINF = TINF/3600.
      REND = REND/100.
      T12=(1.45/1.14)**4*(VOL/(DELTA*GRAV*ZU))**0.333
      T12 = T12/3600.
      T23=(1.45/2.30)**2*(RHOWAT/SIGMA) * VOL**0.6667 *
     1( DELTA * GRAV * ZU )**0.333
      T23 = T23/3600.
      VVL = VOL
      WRITE(6,106) REND
      WRITE(6,110) HINF
      WRITE(6,111) TINF
      WRITE(6,114) T12,T23
      WRITE(6,108)
      WRITE(6,107)
      WRITE(6,102)
      TIMES(1) = 0.
      TS = 0.
C*******
      DO 20 K = 1,NK
C ASSUME THE WIND BLOWS RANDOMLY AT SPEED BETWEEN 0.5 TO 25
C KNOTS PER HOUR.
      CALL RANDU(IX,IY,YFL)
      WIND = YFL * 24.5 + 0.5
      XXX = SIN(0.01745*PHI)
C COMPUTE THE SEA SURFACE CURRENT VELOCITY INDUCED BY THE
C WINDS.
      SCW = 0.0361 * SQRT(WIND)/SQRT(XXX)
      IF( WIND .GT. 11.64 ) SCW = 0.0126*WIND/SQRT(XXX)
C COMPUTE THE OIL SLICK LEEWAY BLOWS BY THE WIND.
      OSL = 0.0199 * WIND
      IF(WIND.GT.5.0.AND.WIND.LT.25.0) OSL=.0179*WIND+0.0196
C CONVERT KNOTS/HR TO METERS/HR :
      WINDV(K)= 1850. * WIND
      SCWV(K) = 1850.*SCW
      OSLV(K) = 1850.*OSL
C SPREAD BY GRAVITY-INERTIA FORCE
      TIME = FLOAT(K)
      T = TIME*15.*60.
      TIME = TIME/4.
      IF (TIME .GE. T12) GO TO 1
      DELT(K) = (ZU*T)**.5
      VLL = VOL/10.**4
      R1 = 10.*( DELTA * GRAV * VLL * T**2 )**0.25*1.14
      HT = VOL/R1**2
      R1 = R1/100.
      RADIUS(K) = R1
      TS = TS + 1.
      GO TO 21
C SPREAD BY GRAVITY-VISCOUS FORCE
  1   AA = ZU**.5
      TIME = FLOAT(K) - TS
      IF(TIME .GT. 24.) TIME=(TIME - 24.)*2.  + 24.
      IF(TIME .GT. 48.) TIME=(TIME - 48.)*3.  + 48.
      T = TIME*3600.
      IF (TIME .GE. T23) GO TO 2
      DELT(K) = (ZU*T)**.5
      R2=1.45*(((DELTA*GRAV*VOL**2*T**1.5)/AA)**.166667)
      HT = VOL/R2**2
      R2 = R2/100.
      RADIUS(K) = R2
      IF( RADIUS(K) .GE. REND ) GO TO 9
      GO TO 21
C SPREAD BY SURFACE TENSION-VISCOUS
```

```
  2    BB = ZU*RHOIL**2
       DELT(K) = (ZU*T)**.5
       R3 = ((SIGMA**2 * T**3  )/  BB )**.25 * 2.30
       HT = VOL/R3**2
       R3 = R3/100.
       RADIUS(K) = R3
       IF( RADIUS(K) .GE. REND ) GO TO 9
       GO TO 21
     9 RADIUS(K) = REND
       HT = VOL/(REND*100.)**2
C
C LOSS DUE TO EVAPORATION
  21   FF = C1*TIME*60./(1.+C2*TIME*60.)
       VOL = (VVL - VVL*FF*0.01)
       VXL(K) = VOL/1000.
C
C  PRINTS THE RADIUS OF OIL SPREAD IN METERS, THE TIME OF
C SPREAD IN HOURS, THE THICKNESS OF OIL AS A FUNCTION OF
C TIME IN CM, THE THICKNESS OF OIL LAYER IN CM, AND THE RE-
C MAINING VOLUME OF OIL AFTER EVAPORATION IN LITERS.
       HTT(K) = HT
       WRITE(6,103) RADIUS(K),TIME,HTT(K),DELT(K),VXL(K),K
       X(K) = ALOG10(TIME)
       Y(K) = ALOG10(RADIUS(K))
       ALPHA = 0.0
       TIMES(K+1) = TIME
C THE ESTUARINE NONTIDAL DRIFT WAS SIMULATED AS A UNIFORM
C CURRENT WITH CONSTANT SPEED APPROX. 65 M/HOURS IN THE
C SOUTH BAY AND 200 M/HOURS IN THE NORTHERN BAY AREA.
       CRAN = 62.500*(TIMES(K+1) - TIMES(K))
       IF( XMV(I) .GE. 16125. .AND. YMV(I) .GE. 51600. )
      1CRAN = 208.3*(TIMES(K+1) - TIMES(K))
      1*(TIMES(K+1) - TIMES(K))
       BETA1 = 0.01745*(YFL*100. + 90. )
       IF( XMV(K).GT.35475. .AND. YMV(K).GT.8063.0 )
      1BETA1 = 0.01745*( YFL*100. + 65. )
       IF( XMV(K).GT.21736. .AND. YMV(K).GT.17737. )
      2BETA1 = 0.01745*( YFL*60. + 65. )
       IF( XMV(K).GT.21736. .AND. YMV(K).GT.38700. )
      3BETA1 = 0.01745*( YFL*100. + 45. )
       IF( XMV(K).GT. 16125. .AND. YMV(K).GT.51600. )
      4BETA1 = 0.01745*( YFL*60. + 160. )
       IF( XMV(K).LE.16125. .AND. YMV(K).LE.51600.0 )
      5BETA1 = 0.01745*( YFL*180. + 90. )
       XCRAN = CRAN*COS(BETA1)
       YCRAN = CRAN*SIN(BETA1)
       IX = IY
       CALL RANDU(IX,IY,YFL)
       BETA =0.01745*(YFL*GAMA1 + GAMA2 )
       IF( XMV(K) .LE. 16125. ) BETA= 0.01745*(YFL*180.+90.)
       IF( XMV(K) .GT. 16125. .AND. YMV(K) .GT. 36280. )
      1BETA = 0.01745*( YFL*GAMA3 + GAMA4 )
       IF( XMV(K) .GT. 16125. .AND. YMV(K) .GT. 51600. )
      2BETA = 0.01745*( YFL*GAMA5 + GAMA6 )
       ROUTE = DSLV(K)*(TIMES(K+1)-TIMES(K))
       XMV(K+1) = XMV(K) + ROUTE*COS(BETA) + XCRAN
       YMV(K+1) = YMV(K) + ROUTE*SIN(BETA) + YCRAN
       IX = IY
C GENERATE RADIUS OF OIL SPREAD.
C********
       DO 30 L = 1,KX
       ALPHA = ALPHA + 360./FLOAT(KX)
       CC(K,L) = XMV(K+1) + RADIUS(K)*COS(ALPHA)
       DC(K,L) = YMV(K+1) + RADIUS(K)*SIN(ALPHA)
  30   CONTINUE
       IF( HTT(K) .LT. 0.010 ) GO TO 22
  20   CONTINUE
C++++++++++++++++++
   22 WRITE(6,112)
       WRITE(6,202)
       DO 50 K=1,NK
       WRITE(6,201) WINDV(K),DSLV(K),SCWV(K),XMV(K+1),
```

```
     2YMV(K+1),K
  50  CONTINUE
      WRITE(6,112)
C PLOT THE SLICK MOVEMENTS INDUCED BY THE WIND AND ITS
C SPREAD.
      NN = NK*KX
      L = 0
      DO 999 II=1,NK
      DO 999 JJ=1,KX
      L = L + 1
C LET CONVERT 50000 METERS EQUAL TO 10 INCHES:
      CCA(L) = CC(II,JJ)
      CCAA(L) = 0.00020*(CCA(L) )
      IF( CCAA(L) .LE. 0.0 ) CCAA(L) = 0.0
      IF( CCAA(L) .GE. 9.0 ) CCAA(L) = 9.0
      DDA(L) = DD(II,JJ)
      DDAA(L) = 0.00020*DDA(L)
      IF( DDAA(L) .LE. 0.0 ) DDAA(L) = 0.0
      IF( DDAA(L) .GE.14.0 ) DDAA(L) = 14.0
 999  CONTINUE
C
C                            P L O T
C>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
C
C PLOT IN A LIN-LIN SCALE THE THICKNESS OF OIL AS A FUNCTION
C OF TIME
      CALL PLOTP(X,HTT,NK,0)
      WRITE(6,112)
C PLOT IN A LIN-LIN SCALE VOLUME AS A FUNCTION OF TIME.
      CALL PLOTP( X,VXL,NK,0 )
      WRITE(6,112)
C PLOT IN A LOG-LOG SCALE THE RADIUS OF SPILL AS A FUNCTION
C OF TIME
      CALL PLOTP(X,Y,NK,0)
C
      REAL XTITLE(2)/'LATI','TUDE'/
      REAL YTITLE(3)/'LONG','ITUD','E   '/
      X1 = 0.0
      X2 = 0.0
      NCX = -8
      SIZEX = 8.
      XMIN = 0.0
      DX = 5000.
      Y1 = 0.0
      Y2 = 0.0
      NCY = 9
      SIZEY = 14.
      YMIN = 0.0
      DY = 5000.
C
C                            D  R  A  W
C
C=================================================================
      NK = NK+1
      CALL PLOTS
      CALL AXIS(X1,X2,XTITLE,NCX,SIZEX, 0.0,XMIN, DX)
      CALL AXIS(Y1,Y2,YTITLE,NCY,SIZEY,90.,YMIN, DY)
      NZ = 0
      DO 911 I=1,NK
      HTT(I) = 0.00020*( XMV(I) )
      DELT(I)= 0.0002*YMV(I)
      NZ = NZ+1
      IF( HTT(I) .LT. 0.0 .OR. DELT(I) .LT. 0.0 ) GO TO 7
      IF( HTT(I).GE.8.0 .OR. DELT(I).GE.14.0) GO TO 7
 911  CONTINUE
   7  CALL LINE(HTT,DELT,NZ, 1, 2 )
      CALL LINE(CCAA,DDAA,NN, 1,-7)
      CALL PLOT(0.0,16.0,-3)
C
      IF( YMV(1) .GE. 36757.5 ) GO TO 555
      IF( XMV(1) .GE. 48165. ) GO TO 556
      IF( YMV(1) .GE. 60850. ) GO TO 557
```

```
      IF( XMV(1).GT.58000. .OR. YMV(1).GT.70900.) STOP
C
C     SOUTHERN BAY
C
      DO 912  I=1,KK
      XQ(I) = XO(I) - 140.
      IF( XQ(I) .LE. 0.0 ) XQ(I) = 0.0
      XQ(I) = XQ(I)*0.0725
      YQ(I) = YO(I)
      IF( YQ(I) .GE. 125. ) YQ(I) = 125.
      YQ(I) = YQ(I)*0.0725
  912 CONTINUE
      SUM = 0.0
      NZ = 0
      DO 401 I=1,NK
      HTT(I) = 0.00039*XMV(I) - 14.0
      DELT(I) = 0.00039*YMV(I)
      IF(HTT(I).LT.0.0. OR.DELT(I).LT.0.0) GO TO 401
      IF(HTT(I).GT.9.0.OR.DELT(I).GT.12.0) GO TO 401
      DZ(I) = ( YMV(I) - YMV(I-1) )**2
      HZ(I) = ( XMV(I) - XMV(I-1))**2
      NZ = NZ+1
      FA = 2.*RADIUS(I )*SQRT( DZ(I) + HZ(I) )
      SUM = SUM + FA
      IF( DELT(I) .LT. 3.5 ) GO TO 666
C CONVERT TO THESIS FORMAT 8.5X11.
      HTT(I) = HTT(I)*0.725
      DELT(I) = DELT(I)*0.725
      IF( HTT(I).GE.3.0 .OR. DELT(I).GE. 8.4 ) GO TO 8
  401 CONTINUE
  8   IF( NZ .LT. 3 ) GO TO 888
      CALL LINE( HTT,DELT,NZ, 1, 2 )
      NM = NZ*KX
      DO 501 I=1,NM
      CCAA(I) = 0.00039*CCA(I) - 14.
      IF( CCAA(I) .LE. 0.0 ) CCAA(I) = 0.0
      IF( CCAA(I) .GT. 4.0 ) CCAA(I) = 4.0
      DDAA(I) = 0.00039*DDA(I)
      IF( DDAA(I) .GE.12.0 ) DDAA(I) = 12.0
C CONVERT TO THESIS FORMAT 8.5X11.
      CCAA(I) = CCAA(I)*0.725
      DDAA(I) = DDAA(I)*0.725
  501 CONTINUE
      SUM1 = 0.0001*SUM
      WRITE(6,304) SUM1
      WRITE(6,303) RADIUS(NZ), NZ
      CALL LINE( XQ,YQ,KK,1 , 1 )
      CALL SYMBOL( 2.3, 9.4,.14,'EAST SOUTHERN BAY',.0,17 )
      CALL LINE(CCAA,DDAA,NM, 1,-7 )
      CALL PLOT(0.0,12.0,-3)
C
  888 DO 913 I=1,KK
      XS(I) = XO(I) - 60.
      IF( XS(I) .LE. 0.0 )  XS(I) = 0.0
      IF( XS(I) .GE. 90. ) XS(I) = 90.
      XS(I) = XS(I)*0.0725
      YS(I) = YO(I) - 50.
      IF( YS(I) .LE. 0.0 ) YS(I) = 0.0
      IF( YS(I) .GE. 120. )  YS(I) = 120.
      YS(I) = YS(I)*0.0725
  913 CONTINUE
      SUM = 0.0
      HTT(1) = 0.00039*XMV(1) - 6.0
      DELT(1) = 0.00039*YMV(1) - 5.0
      IF( HTT(1).GE. 0.0 .AND. DELT(1).GE. 0.0 ) NZ = 0
      DO 701 I=1,NK
      HTT(I) = 0.00039*XMV(I) - 6.0
      DELT(I) = 0.00039*YMV(I) - 5.0
      IF(HTT(I).LT.0.0. OR.DELT(I).LT.0.0) GO TO 701
      IF(HTT(I).GT.9.0. OR.DELT(I).GT.12.0) GO TO 701
      DZ(I) = ( YMV(I) - YMV(I-1) )**2
      HZ(I) = ( XMV(I) - XMV(I-1))**2
```

```
      NZ = NZ+1
      FA = 2.*RADIUS(I )*SQRT( DZ(I) + HZ(I) )
      SUM = SUM + FA
      IF( HTT(I).GT.5.25.AND.DELT(I).GT.9.0 ) DELT(I)=9.0
      IF( HTT(I).GT.8.0.AND.DELT(I).GT.6.5 ) DELT(I)=6.5
C CONVERT TO THESIS FORMAT 8.5X11.
      HTT(I) = HTT(I)*0.725
      DELT(I) = DELT(I)*0.725
      IF( HTT(I) .LT. 2.4 .AND.DELT(I) .LT. 7.3 ) GO TO 3
      IF(HTT(I).GE.5.5 .AND. DELT(I).GE.5.0 ) GO TO 3
  701 CONTINUE
    3 CALL LINE(HTT,DELT,NZ, 1, 2 )
      NM = NZ*KX
      DO 601 I=1,NM
      CCAA(I) = 0.00039*CCA(I) - 6.
      IF( CCAA(I) .LE. 0.0 ) CCAA(I) = 0.0
      IF( CCAA(I) .GE. 9.0 ) CCAA(I) = 9.0
      DDAA(I) = 0.00039*DDA(I) - 5.0
      IF( DDAA(I) .GE. 12.0 ) DDAA(I) = 12.0
      IF( CCAA(I).GT.5.25.AND.DDAA(I).GT. 9.0) DDAA(I)= 9.0
      IF( CCAA(I).GT.8.0.AND.DDAA(I).GT.6.5 ) DDAA(I)= 6.5
C CONVERT TO THESIS FORMAT 8.5X11.
      CCAA(I) = CCAA(I)*0.725
      DDAA(I) = DDAA(I)*0.725
  601 CONTINUE
      SUM2 = 0.0001*SUM
      WRITE(6,304) SUM2
      WRITE(6,303) RADIUS(NZ), NZ
      CALL SYMBOL( 2.3, 9.2,.14,'WEST SOUTHERN BAY',.0,17 )
      CALL LINE( XS, YS,KK, 1, 1 )
      CALL LINE(CCAA,DDAA,NM, 1,-7 )
      CALL PLOT(0.0,12.0,-3)
C
C
C     NORTHERN BAY
C
  556 DO 916 I=1,KK
      XV(I) = XO(I) - 140.
      IF( XV(I) .LE. 0.0 ) XV(I) = 0.0
      XV(I) = 0.0725*XV(I)
      YV(I) = YO(I) - 230.
      IF( YV(I) .LE. 0.0 ) YV(I) = 0.0
      YV(I) = 0.0725*YV(I)
  916 CONTINUE
      SUM = 0.0
      NZ = 0
      DO 705 I=1,NK
      HTT(I) = 0.00039*XMV(I) - 14.0
      DELT(I) = 0.00039*YMV(I) -23.0
      IF(HTT(I).LT.0.0. OR.DELT(I).LT.0.0) GO TO 705
      DZ(I) = ( YMV(I) - YMV(I-1) )**2
      HZ(I) = ( XMV(I) - XMV(I-1))**2
      NZ = NZ+1
      FA = 2.*RADIUS(I )*SQRT( DZ(I) + HZ(I) )
      SUM = SUM + FA
C CONVERT TO THESIS FORMAT 8.5X11.
      HTT(I) = HTT(I)*0.725
      DELT(I) = DELT(I)*0.725
      IF( HTT(I).GT.6.5 .OR. DELT(I).GT.5.0 ) GO TO 6
  705 CONTINUE
    6 IF( NZ .LT. 3 ) GO TO 666
      CALL LINE( HTT,DELT,NZ, 1, 2 )
      NM = NZ*KX
      DO 602 I=1,NM
      CCAA(I) = 0.00039*CCA(I) - 14.
      IF( CCAA(I) .LE. 0.0 ) CCAA(I) = 0.0
      IF( CCAA(I) .GE. 9.0 ) CCAA(I) = 9.0
      DDAA(I) = 0.00039*DDA(I)- 23.
      IF( DDAA(I) .LE. 0.0 ) DDAA(I) = 0.0
      IF( DDAA(I) .GE. 7.0 ) DDAA(I) = 7.0
C CONVERT TO THESIS FORMAT 8.5X11.
      CCAA(I) = CCAA(I)*0.725
```

```
      DCAA(I) = DDAA(I)*0.725
  602 CONTINUE
      SUM5 = 0.0001*SUM
      WRITE(6,304) SUM5
      WRITE(6,303) RADIUS(NZ), NZ
      CALL SYMBOL( 2.1,5.43,.14,'EAST NORTHERN BAY',.0,17 )
      CALL LINE( XV,YV,KK, 1, 1 )
      CALL LINE(CCAA,DDAA,NM, 1,-7 )
      CALL PLOT( 0.0,10.0,-3 )
C
  557 DO 915 I=1,KK
      XU(I) = XO(I) - 50.
      IF( XU(I) .LE. 0.0 ) XU(I) = 0.0
      IF( XU(I) .GE. 90. ) XU(I) = 90.
      XU(I) = 0.0725*XU(I)
      YU(I) = YO(I) - 230.
      IF( YU(I) .LE. 0.0 ) YU(I) = 0.0
      YU(I) = 0.0725*YU(I)
  915 CONTINUE
      SUM = 0.0
      HTT(1) = 0.00039*XMV(1) - 5.0
      DELT(1) = 0.00039*YMV(1) - 23.0
      IF( HTT(1).GE. 0.0 .AND. DELT(1).GE. 0.0 ) NZ = 0
      DO 704 I=1,NK
      HTT(I) = 0.00039*XMV(I) - 5.0
 \    DELT(I) = 0.00039*YMV(I) -23.0
      IF( HTT(I) .LE. 1.0 ) HTT(I)=1.0
      IF( DELT(I).GE. 5.8 ) DELT(I)=5.8
      IF(HTT(I).LT.0.0. OR.DELT(I).LT.0.0) GO TO 704
      IF(HTT(I).GT.9.0. OR.DELT(I).GT. 6.0) GO TO 704
      CALL SYMBOL( 2.2, 6.8,.14,'CENTRAL BAY',.0,11 )
      DZ(I) = ( YMV(I) - YMV(I-1) )**2
      HZ(I) = ( XMV(I) - XMV(I-1))**2
      NZ = NZ+1
      FA = 2.*RADIUS(I )*SQRT( DZ(I) + HZ(I) )
      SUM = SUM + FA
C CONVERT TO THESIS FORMAT 8.5X11.
      HTT(I) = HTT(I)*0.725
      DELT(I) = DELT(I)*0.725
      IF( HTT(I) .LE. 0.72.OR. DELT(I) .GE. 3.75) GO TO 5
  704 CONTINUE
   5  CALL LINE( HTT,DELT,NZ, 1, 2 )
      NM = NZ*KX
      DO 604 I=1,NM
      CCAA(I) = 0.00039*CCA(I) - 5.
      IF( CCAA(I) .LE. 1.0 ) CCAA(I) = 1.0
      IF( CCAA(I) .GE. 9.0 ) CCAA(I) = 9.0
      DDAA(I) = 0.00039*DDA(I)- 23.
      IF( DDAA(I) .LE. 0.0 ) DDAA(I) = 0.0
      IF( DDAA(I) .GE. 5.8 ) DDAA(I) = 5.8
C CONVERT TO THESIS FORMAT 8.5X11.
      CCAA(I) = CCAA(I)*0.725
      DDAA(I) = DDAA(I)*0.725
  604 CONTINUE
      SUM4 = 0.0001*SUM
      WRITE(6,304) SUM4
      WRITE(6,303) RADIUS(NZ), NZ
      CALL LINE( XU, YU,KK, 1, 1 )
      CALL SYMBOL( 2.1,5.43,.14,'WEST NORTHERN BAY',.0,17 )
      CALL LINE(CCAA,DDAA,NM, 1,-7 )
      CALL PLOT( 0.0,10.0,-3 )
C
C     CENTRAL BAY.
C
  555 DO 914 I=1,KK
      XT(I) = XO(I) - 40.
      IF( XT(I) .LE. 0.0 )  XT(I) = 0.0
      IF( XT(I) .GE. 90. ) XT(I) = 90.
      XT(I) = 0.0725*XT(I)
      YT(I) = YO(I) - 145.
      IF( YT(I) .LE. 0.0 ) YT(I) = 0.0
      IF( YT(I) .GE. 90. ) YT(I) = 90.
```

```
      YT(I) = 0.0725*YT(I)
  914 CONTINUE
      SUM = 0.0
      HTT(1) = 0.00039*XMV(1) - 4.0
      DELT(1) = 0.00039*YMV(1) - 14.5
      IF( HTT(1).GE. 0.0 .AND. DELT(1).GE. 0.0 ) NZ = 0
      DO 703 I=1,NK
      HTT(I) = 0.00039*XMV(I) - 4.0
      DELT(I) = 0.00039*YMV(I) -14.5
      IF(HTT(I).LT.0.0. OR.DELT(I).LT.0.0) GO TO 703
      IF(HTT(I).GT.9.0. OR.DELT(I).GT. 9.0) GO TO 703
      DZ(I) = ( YMV(I) - YMV(I-1) )**2
      HZ(I) = ( XMV(I) - XMV(I-1))**2
      NZ = NZ+1
      FA = 2.*RADIUS(I )*SQRT( DZ(I) + HZ(I) )
      SUM = SUM + FA
      IF(HTT(I).LT.2.125.AND.DELT(I).GT.2.875) HTT(I)=2.125
C CONVERT TO THESIS FORMAT 8.5X11.
      HTT(I) = HTT(I)*0.725
      DELT(I) = DELT(I)*0.725
      IF( HTT(I).GE.5.6 .OR. DELT(I).GE. 6.5 ) GO TO 4
  703 CONTINUE
    4 CALL LINE(HTT,DELT,NZ, 1, 2 )
      NM = NZ*KX
      DO 603 I=1,NM
      CCAA(I) = 0.00039*CCA(I) - 4.
      IF( CCAA(I) .LE. 0.0 ) CCAA(I) = 0.0
      IF( CCAA(I) .GT. 7.8 ) CCAA(I) = 7.8
      DDAA(I) = 0.00039*DDA(I)- 14.5
      IF( DDAA(I) .LE. 0.0 ) DDAA(I) = 0.0
      IF(CCAA(I).LT.2.125.AND.DDAA(I).GT.2.875) CCAA(I)=2.12
      IF( DDAA(I) .GE. 9.0 ) DDAA(I) = 9.0
C CONVERT TO THESIS FORMAT 8.5X11.
      CCAA(I) = CCAA(I)*0.725
      DDAA(I) = DDAA(I)*0.725
  603 CONTINUE
      SUM3 = 0.0001*SUM
      WRITE(6,304) SUM3
      WRITE(6,303) RADIUS(NZ), NZ
      CALL LINE( XT,YT,KK, 1, 1 )
      CALL LINE(CCAA,DDAA,NM, 1,-7 )
      CALL PLOT(0.0,12.0,-3)
C
C
C
  666 DO 10 I=1,KK
      XP(I) = .0306*XO(I)
      YP(I) = .0306*YO(I)
   10 CONTINUE
      DO 667 J=1,N
      AX(J) = AX(J)*0.78
      AY(J)=AY(J)*0.78
 667  CONTINUE
      DO 668 K=1,M
      XR(K) = XR(K)*0.78
      YR(K) = YR(K)*0.78
  668 CONTINUE
      CALL LINE( XP, YP, KK ,-1,1)
      CALL SYMBOL(1.44,10.0,.14,
     1'ANALYSIS OF OIL SPILL MOVEMENT',.0,30 )
      CALL SYMBOL(1.75, 9.7,.14,'IN SAN FRANCISCO BAY AREA',
     2.0,25 )
      CALL SYMBOL(0.77, 9.4,.14,
     1'AS PREDICTED BY ESTUARINE NON TIDAL DRIFT',0.0,41 )
      CALL SYMBOL(5.8, 7.95,0.07,'SUISUN BAY',0.0,10)
      CALL SYMBOL(0.20, 7.74,.07,'38N',0.0,3)
      CALL SYMBOL(2.30,7.78,.07,'SAN PABLO BAY',0.0,13)
      CALL SYMBOL(5.06, 7.54,.07,'* BENICIA',0.0,9)
      CALL SYMBOL(3.70,5.60,.07,'* ALBANY',0.0,8)
      CALL SYMBOL(4.40,4.10,.14,'ALAMEDA',0.0,7)
      CALL SYMBOL(2.17,3.73,0.07,'HUNTER POINT',0.0,12)
      CALL SYMBOL(3.5,2.72,.07,'SAN FRANCISCO BAY',0.0,17)
```

```
      CALL SYMBOL(3.50,1.75,.07,'FOSTER CITY *',.0,13)
      CALL SYMBOL(4.55,0.4,0.14,'PALO ALTO',0.0,9)
      CALL LINE(AX,AY, N, 1,1)
      CALL LINE(XR,YR,M, 1,1)
      CALL PLOT(0.0,14.0,-3)
      CALL PLOTE
C=================================================================
C
C
      STOP
      END
//GO.SYSIN DD *
```

APPENDIX B

COMPUTER SIMULATION PROGRAM OF
THE SOCIAL COST OF THE LOSSES IN THE RECREATION
ACTIVITIES AND THE COMMERCIAL FISHING ACTIVITIES

```
//HAN1874 JOB (2696,1446,RL44),'MUDJIARDJO SMC 1874'
// EXEC FORTCLGP,REGION.GO=180K
//FORT.SYSIN DD *
      DIMENSION XD(50), YD(50), P(50), TX(10),TY(10)
      DIMENSION XH(50), YH(50), XC(50), YC(50), YCC(50)
      DIMENSION XE(10), YE(10), PYY(10), V(10), SC(10)
C INITIAL INPUT DATA
      READ(5,89) ALFA,BEFA,PX,PY,AK,BK
      K = 4
C READ VOLUME SPILLED IN LITERS.
      READ(5,83)  (V(J), J=1,K)
      WRITE(6,85)
      WRITE(6,82) (V(J), J=1,K)
C
   79 FORMAT(/////)
   80 FORMAT(/,10X,'NO:(',I3,')',2X,'SOCIAL COST=', F12.2,
     12X,' VOL. SPILLED LTRS=',F12.1 )
   81 FORMAT(/,58X,'AH=',F9.2,3X,'BH=',F9.2)
   82 FORMAT( /,10X,5F12.1 )
   83 FORMAT( 5F12.1 )
   84 FORMAT(/,10X,'PYY(',I3,') EQ. PRICE LEVEL OF Y:',F8.2)
   85 FORMAT(/,4X,' INPUT DATA: ' )
   86 FORMAT('1',4X,'COORD. PTS OF PROD.FNC, MAX. PROFIT',
     1' LINE, OPTIMAL PROFIT LINE AND WELFARE FUNCTION' )
   87 FORMAT(//, 4X,' EQUILIBRIUM POINT: ' )
   88 FORMAT(5X,'ALPHA=',F4.2,3X,'BETA=',F4.2,3X,'PX=',
     1F8.2,3X,'PY=',F8.2,3X,'AK=',F9.2,3X,'BK=',F9.2 )
   89 FORMAT( 2F4.2,2F8.2,2F9.2 )
   90 FORMAT(/,10X,F9.1,3X,F9.1,5X,F9.1,5X,F9.1,3X,F12.1 )
   91 FORMAT(/,5X,'$ PROFIT OF X & Y= ',F12.2,3X,
     1'WELFARE INITIAL STATUS:',F8.1 )
   92 FORMAT(  /,10X,F8.2,3X,4F9.1 )
   93 FORMAT(/,10X,'X UNITS:',F9.1,3X,'Y UNITS:',F9.1,3X,
     1'J=',I3 )
   94 FORMAT('1','  COORDINATE POINTS OF SUPPLY AND DEMAND',
     2' CURVE' )
      N = 25
      M = 20
      CW = 2.50
      XH(1) = 0.0
      ZETA = ALFA + BEFA
      DO 1004 J=1,K
C PRODUCTION FUNCTION AS A FUNCTION OF VOLUME SPILLED.
      AK1 =(V(J)/10.**6)**2
      AH = AK*(0.9*EXP(-AK1)+ 0.1)
      BK1 =(5.*V(J)/10.**6)**2
      BH = BK*(0.75*EXP(-BK1) + 0.25)
      WRITE(6,79)
      WRITE(6,88) ALFA,BEFA,PX,PY,AK,BK
      WRITE(6,81) AH, BH
      XUP = PX*AH**2
      YUP = PY*BH**2
      QP = SQRT(PX**2*AH**2+PY**2*BH**2)
      RL = XUP/QP
      RM = YUP/QP
C EQUILIBRIUM POINT.
      XE(J) = SQRT(ALFA*AH**2/ ZETA )
      YE(J) = SQRT(BEFA*BH**2/ ZETA )
C MAXIMUM PROFIT
      PROFT= PX*(XUP/QP) + PY*(YUP/QP)
```

```
C WELFARE STATUS VALUE
      WWX=ALFA*PROFT/(PX*ZETA)
      WWY=BEFA*PROFT/(PY*ZETA)
      WS = CW*XE(J)**ALFA * YE(J)**BEFA
      WRITE(6,87)
      WRITE(6,93) RL,RM, J
      WRITE(6,93) WWX,WWY, J
      WRITE(6,93) XE(J), YE(J), J
      WRITE(6,91) PROFT,WS
C MOVING OF PRICE TO EQUILIBRIUM STATE.
      BUL = BH**2 - YE(J)**2
      IF( BUL.LT. 0.0) BUL=0.0
      PYY(J)=YE(J)*PX*AH/(BH*SQRT(BUL))
      WRITE(6,84) J,PYY(J)
      WRITE(6,86)
      DO 1000 I=1,N
C PRODUCTION POSSIBILITIES CURVE
      QRS = BH**2 - (BH**2/AH**2)*XH(I)**2
      IF( QRS .LT. 0.0) QRS = 0.0
      YH(I) = SQRT(QRS)
C BUDGET CONSTRAINT OR PROFIT FUNCTION
      YC(I) = (PROFT - PX*XH(I))/PY
      IF( YC(I) .LT. 0.0 ) YC(I)=0.0
C NEW OPTIMAL PROFIT LINE
      PROFC=PX*XE(J) + PYY(J)*YE(J)
      YCC(I)=(PROFC - PX*XH(I))/PYY(J)
      IF( YCC(I).LT.0.0) YCC(I)=0.0
C WELFARE CURVE
      XH(I+1) = XH(I) + 50.
      XD(I) = XH(I)
      IF( XD(I) .EQ. 0.0 ) XD(I) = 10.0
      YD(I) = (WS/(CW*XD(I)**ALFA))**(1./BEFA)
      WRITE(6,90) XH(I),YH(I),YC(I),YCC(I),YD(I)
 1000 CONTINUE
      WRITE(6,94)
C
C CONVERT TO THESIS FORMAT
      DO 1001 I=1,N
      XH(I) = 0.00005*XH(I) + 0.5
      IF( XH(I).GT.6.5) XH(I)=6.5
      YH(I) = 0.00005*YH(I) + 0.5
      IF( YH(I).GT.9.0) YH(I)=9.0
      YC(I) = 0.00005*YC(I) + 0.5
      IF( YC(I).GT.9.0) YC(I)=9.0
      XD(I) = 0.00005*XD(I) + 0.5
      IF( XD(I).GT.6.5) XD(I)=6.5
      YD(I) = 0.005*YD(I) + 0.5
      IF( YD(I).GT.9.0) YD(I)=9.0
      YCC(I)= 0.00005*YCC(I)+ 0.5
      IF( YCC(I).GT.9.0 ) YCC(I) = 9.0
 1001 CONTINUE
      TX(1) = 0.5
      TY(1) = 0.5
      TX(2) = 6.5
      TY(2) = 0.5
      TX(3) = 6.5
      TY(3) = 9.0
      TX(4) = 0.5
      TY(4) = 9.0
      TX(5) = 0.5
      TY(5) = 0.5
      CALL PLOTS
      CALL SYMBOL( 2.5,0.0,.14,' X UNIT PRODUCED ',0.0,17 )
      CALL SYMBOL( 0.0,2.0,.14,' Y UNIT PRODUCED ',90.0,17 )
      CALL LINE( TX,TY,5,1,1 )
      CALL SYMBOL(4.0,8.0,.07,'+ PROD. POSS CURVE ',0.,19)
      CALL SYMBOL(4.0,7.8,.07,'- MAX PROFIT LINE ',0.0,18)
      CALL SYMBOL(4.0,7.6,.07,'* WELFARE CURVE ',0.0,16)
      CALL LINE( XH,YH, N,1,2 )
      CALL LINE( XH,YC, N,1,-7 )
      CALL LINE( XH,YCC,N,1,6 )
      CALL LINE( XD,YD, N,1,5 )
```

```
      CALL PLOT( 0.0,12.0,-3 )
C
C
      P(1) = 5.
      DO 1002 I=1,M
C SUPPLY CURVE
      XH(I) = AH**2*P(I)/PROFC
      YH(I) = BH**2*P(I)/PROFC
C DEMAND CURVE
      XC(I) = ALFA*PROFC/ZETA*(1./P(I))
      YC(I) = BEFA*PROFC/ZETA*(1./P(I))
      WRITE(6,92) P(I),XH(I),YH(I),XC(I),YC(I)
      P(I+1) = P(I) + 5.
 1002 CONTINUE
C
C CONVERT TO THESIS FORMAT
      DO 1003 I=1,M
      P(I) = 0.025*P(I) + 0.5
      IF( P(I).GT.9.0) P(I)=9.0
      XH(I) = 0.00005*XH(I) + 0.5
      IF(XH(I).GT.6.5) XH(I) = 6.5
      XC(I) = 0.00005*XC(I) + 0.5
      IF(XC(I).GT.6.5) XC(I) = 6.5
      YC(I) = 0.00005*YC(I) + 0.5
      IF(YC(I).GT.6.5) YC(I) = 6.5
      YH(I) = 0.00005*YH(I) + 0.5
      IF(YH(I).GT.6.5) YH(I) = 6.5
 1003 CONTINUE
      CALL SYMBOL( 2.5,0.0,.14,' X UNIT PRODUCED ',0.0,17 )
      CALL SYMBOL( 0.0,2.0,.14,' PRICE PER UNIT PRODUCT ',
     190.0,24 )
      CALL SYMBOL(4.0,8.2,.07,' + SUPPLY CURVE ',0.0,16)
      CALL SYMBOL(4.0,8.0,.07,' - DEMAND CURVE ',0.0,16)
      CALL LINE( XC,P, M,1,1 )
      CALL LINE( XH,P,M,1,2 )
      CALL LINE( TX,TY,5,1,1 )
      CALL PLOT( 0.0,12.0,-3 )
C
      CALL SYMBOL( 2.5,0.0,.14,' Y UNIT PRODUCED ',0.0,17 )
      CALL SYMBOL( 0.0,2.0,.14,' PRICE PER UNIT PRODUCT ',
     190.0,24 )
      CALL SYMBOL(4.0,8.2,.07,' + SUPPLY CURVE ',0.0,16)
      CALL SYMBOL(4.0,8.0,.07,' - DEMAND CURVE ',0.0,16)
      CALL LINE( YC,P, M,1,1 )
      CALL LINE( YH,P, M,1,2 )
      CALL LINE( TX,TY,5,1,1 )
      CALL PLOT( 0.0,12.0,-3 )
      CALL PLOTE
 1004 CONTINUE
C
C
C SOCIAL COST OF RECREATION ACTIVITIES & COMMERCIAL FISHING
C ACTIVITIES (AND RELATED INDUSTRIES)
C
      WRITE(6,79)
      DO 1005 J=1,K
      SC(J) = PX*(XE(1) - XE(J)) + PYY(1)*(YE(1) - YE(J))
      WRITE(6,80) J, SC(J), V(J)
 1005 CONTINUE
      STOP
      END
//GO.SYSIN DD *
```

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